THE FINAL REPORT OF THE SPS ENERGY CONVERSION AND POWER MANAGEMENT WORKSHOP

February 5-7, 1980
Von Braun Civic Center
Huntsville, Alabama

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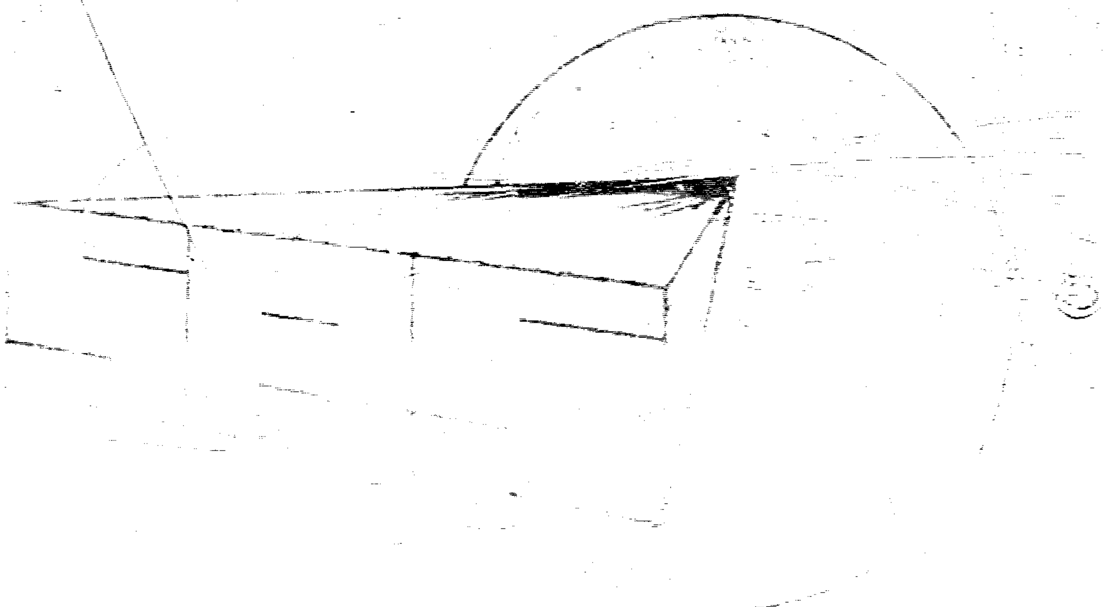

June 1980

Prepared for the
Advanced Systems Office
Program Development Directorate
Marshall Space Flight Center
Huntsville, Alabama

Prepared by the
Johnson Environmental and Energy Center
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Reviewed and Approved by:

David L. Christensen
Senior Research Associate

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FOREWORD

This report represents work performed under NASA contract NAS8-33132. Mr. Charles H. Guttman of Marshall Space Flight Center is the Task Coordinator for the contract period. Mr. David L. Christensen of the University of Alabama in Huntsville is the Project Manager.

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I. INTRODUCTION

In this time of dwindling natural resources and increased global conflict, more and more people are looking to space for solutions to the problems that beset mankind. It is no coincidence that the most popular TV series, the most popular movie, and the largest selling category of books deal with the exploitation and exploration of space. Conflict between nations is driven primarily by economic forces; the need for raw materials, for more land to accommodate growing populations, for more energy. Space offers unlimited sources of energy and raw materials and can be adapted to accommodate a vastly expanded human population. There is a growing realization, especially in industrialized nations, that mankind must develop the resources of space or face his own extinction.

The satellite power system (SPS) program represents a major step forward toward utilizing the resources of space to supply man's energy needs. In the twelve years since the SPS was first proposed a considerable amount of study and evaluation has been undertaken. To date no major problems have been uncovered which would make the concept unfeasible. Instead additional alternatives have been proposed for energy conversion in space and for energy transmission to Earth. The scope of the SPS program is enormous. The idea of building miles-long satellites in geosynchronous orbit and beaming converted solar energy to earth for introduction into the electrical power grid staggers the imagination. SPS is now considered seriously by much of the technical community and many political leaders as a viable future candidate for generating large amounts of electric power.

In 1977 a four year study, the Concept Development and Evaluation Program, was initiated by the U.S. Department of Energy and the National Aeronautics and Space Administration. As part of this program, a series of peer reviews were carried out within the technical community to allow available information on SPS to be sifted, examined and, if need be, challenged. The SPS Energy Conversion and Power Management Workshop, held in Huntsville, Alabama, February 5-7, 1980, was one of these reviews. The results of studies in this particular field were presented to

an audience of carefully selected scientists and engineers. This first report summarizes the results of that peer review. It is not intended to be an exhaustive treatment of the subject. Rather, it is designed to look at the SPS energy conversion and power management options in breadth, not depth, to try to foresee any troublesome and/or potentially unresolvable problems and to identify the most promising areas for future research and development. Workshop participants are listed in Table 1.1.

J. Richard Williams, Ph.D.
Workshop Chairman

TABLE 1.1 Workshop Participants

WORKSHOP CHAIRMAN

J. Richard Williams, Dean of Engineering, University of Idaho

PHOTOVOLTAICS WORKING GROUP

Martin Wolf (Chairman), Dept. of Electrical Engineering, Univ. of Pennsylvania
Richard Alberts, Research Triangle Institute
Charles E. Backus, Asst. Dean of Engineering, Arizona State University
Henry W. Brandhurst, Jr., Lewis Research Center, NASA
Denis Curtin, Asst. Manager, Comsat Laboratory
Sandy Friedlander, Aerospace Corporation
James M. Harris, Principal Scientist, Rockwell International
Peter Illes, Applied Solar Energy Inc.
S. Kamath, Hughes Research Laboratories
James Lazar, Argonne National Laboratories
Arthur A. Nussberger, Rockwell International
Peter Richardson, Planning Research Corporation
John Scott-Monck, Jet Propulsion Laboratory
Calvin C. Silverstein, Westinghouse
Richard Stirn, Jet Propulsion Laboratory
Joseph Wise, Air Force Aerospace Propulsion Laboratory
Solomon Zwerdling, Jet Propulsion Laboratory

SOLAR THERMAL WORKING GROUP

Abraham Hertzberg (Chairman), University of Washington
Bud Brux, Rockwell International
Robert E. English, Lewis Research Center, NASA
J. Pres Layton, Princeton University (retired)
Thomas Mahefkey, Air Force Aerospace Propulsion Laboratory
John M. Hedgepeth, Astro Research Corporation
Jim Ott, Novar Electronics
C. Byron Winn, Dept. of Mechanical Engineering, Colorado State University

POWER DISTRIBUTION AND MANAGEMENT WORKING GROUP

Arthur D. Schoenfeld (Chairman), Asst. Manager, TRW
Reynolds DelGado, Houston Power and Lighting Co.
John Freeman, Space Physics and Astronomy Dept., Rice University
Albert Gordon, Polyscientific Inc.
Frank Mandors, Ball Aerospace Systems Div., Ball Bros.
Ira Myers, Lewis Research Center, NASA
James Rearns, Manager, Aerospace Power Division, WPAFB

2. PHOTOVOLTAIC CONVERSION

2.0 Introduction

The work in the preceding SPS studies and the proposed GBED program, to be conducted until 1986, have been reviewed as far as they relate to the photovoltaic approach to the Energy Conversion System for SPS. The examination was carried out with the viewpoint that the SPS will be a cost effective electrical power source in competition with fossil and nuclear fueled base-load plants, as well as with various types of future terrestrial solar photovoltaic power systems. The attainment of a set of certain design parameters for the conversion system is critical to assuring this competitiveness, and the proof of the feasibility of attaining these design parameters at the earliest possible time is therefore important. Consequently, the planning of the GBED program has been examined primarily for its potential of permitting the evaluation of the most important feasibility conditions by the end of this program (1986).

It has been found that a number of important design parameters are interdependent, particularly those involving the photovoltaic array, and that only the concommitent attainment of acceptable levels of all these parameters can serve as demonstration of feasibility. Examples are cell efficiency, thickness, and radiation resistance. Also, certain tasks can be meaningfully carried out only in sequence. Thus, the development of suitable candidate cell/blanket designs meeting the combined performance/mass/life design parameters, as verified in ground tests, should precede space certification testing, as well as the development of manufacturing methods.

2.1 Critical Issues

The following items have been determined to be critical issues which require primary attention is the GBED program:

2.1.1 Resource Issues

2.1.1.1 Gallium Arsenide Alternative:

- Gallium availablity does not appear to be a limiting factor for the "year 2000" time period, based on studies done to date by Rockwell
- Contact metallurgy must be changed to use of non-noble metals. Alternatives appear to exist in adequate supply
- Sources of metalorganic starting materials are inadequate now, but should be available when needed (This is a processing industry capacity problem)

2.1.1.2 Silicon Alternative:

- Contact metallurgy of space power cells must be changed to the use of non-noble metals, but work on this problem is already part of the terrestrial program

2.1.1.3 Summary

- There are no resource critical issues needing solution or study in GBED

2.1.2 Performance Demonstration Issues

2.1.2.1 Gallium Arsenide Alternative:

- Existence of a suitable film-type solar cell
- Supporting element for the cell
- Demonstration of 18% efficiency (AMO) in a cell 10 microns or less thick and of 10 cm^2 area or greater, on a thin, large area, potentially inexpensive substrate that is capable of meeting SPS weight and cost goals

- As a milestone to the above point, achievement of 16% efficiency in an adequately similar cell/substrate/cover structure within 2 years to permit starting of stability tests
- Development of cells with contacts that are "weldable" and the use of non-noble and non-magnetic metals (trace use of noble metals is acceptable)
- Achievability of 16.2% end-of-life efficiency after 30 years, which requires radiation resistance or annealing
- Preliminary manufacturability studies to show that the developed blanket structure is not incompatible with SPS cost goals

2.1.2.2 Silicon Alternative:

- Demonstration of 16% efficiency (AMO) in 50 micron thick cells of 25 cm^2 or greater area capable of meeting the radiation resistance and/or annealing requirements for SPS within 3 years
- Development of weldable, non-noble, non-magnetic contacts, capable of surviving annealing temperatures
- Achievability of 14.4% end-of-life efficiency after 30 years (increased radiation resistance or annealing)

2.1.2.3 Blanket

- Demonstrate a blanket design that is capable of meeting the SPS design goals (W/kg, T, compatible cost)

2.1.3 Performance Stability Issues

- Subject cells to a qualification test program with emphasis on a radiation damage anneal program (including critical evaluation and assessment)

- Demonstrate annealing to 90% P_{EOL}/P_o of 0.9 or greater in GaAs and Si as function of: particle-type, flux, temperature, concentration ratio, fabrication technique, and n/p or p/n cell type
- Develop and conduct an accelerated testing program to demonstrate 30 year life
- Demonstrate that end-of-life blanket power densities of 300 W/m^2 in the GaAs alternative and 150 W/m^2 in the Si alternative are achievable (80% SPS goal, Rockwell program)
- Conduct basic research and solar cell development programs to understand and eliminate (or at least reduce) radiation damage in Si and GaAs
- Plan and conduct synchronous orbit flight tests (may be after 1986)

2.1.4 Advanced Concepts Alternatives:

- Demonstrate 25% efficient AMO thin film cascade solar cell and show a potential for 35% efficiency
- Investigate alternative advanced photovoltaic concepts leading to 50% conversion efficiency

2.2 Recommendations for the GBED Phase

- The use of concentration ratio 1 with the silicon solar cells should be re-evaluated in light of recent cell developments which resulted in considerably reduced absorptivity/emissivity ratios, permitting lower temperature operation
- To permit evaluation of the impacts of potential changes in some of the cell or blanket goal parameters which may result from the GBED program, the systems analyses will need to be expanded during the GBED period to provide sensitivity data

- As a minimum, regardless of whether or not other parts of this plan are carried out, the GBED program should adequately address the critical need for a space-worthy solar cell encapsulation/blanket-support system
- The SPS system concept should be exposed to the technical community who will be charged with the responsibility of designing and fabricating this system. To accomplish this, there should be a continuing series of peer review workshops during the GBED phase of the SPS program, utilizing experts from the various technology areas of potential concern
- Based on this very brief examination of the challenges presented by the SPS concept, it is felt that the proposed GBED plan is not sufficiently detailed to allow a meaningful assessment of the viability of the SPS concept to be made in 1986. A modified GBED photovoltaic conversion plan, reflecting the above listed critical issues, is provided
- The goals outlined here for the GBED phase are rather ambitious, but necessary to permit assessment of SPS viability by 1986. In order to accomplish what has been recommended, funding levels well in excess of what is proposed for the present GBED program will be required. The time available did not permit preparation of any type of cost estimate. However, feelings have been expressed that, in the best case, the needed funding might be a factor of three greater than planned so far, and, in the worst case, an order of magnitude greater

2.3 Technical Discussion

The nature of the problems in solar cell device development and in blanket development, the latter with its systems integration aspects, as well as the experience base of the experts present, were found to differ substantially. Thus, these two aspects were considered separately in simultaneous sessions, with several joint meetings for integration.

FIGURE 2.2.1

RECOMMENDED GBED PHOTOVOLTAIC CONVERSION PLAN

	Notes	81 82 83 84 85 86
<u>GaAs Cells</u>		
Preliminary cell development	a	XXXXXXXXXXXXXXXXXXXX
Cell stability testing	b	XXXXXXXX
Cell development for feasibility demonstration	c	XXXXXXXXXXXXXXXXXXXXXXX
Stability testing of experimental modules	d	XXXXXXXXXX XXXXXXXXX
Preparation for flight test of experimental modules	e	XXXXXXXXXXXXXXXXXXXXXXX
Experimental module flight test	f	XXXXXXXXXXXXXX
Radiation damage/annealing study	g	XXXXXXXXXXXXXXXXXXXXXXXXXXXXX
Manufacturability evaluation	h	XXXXXX
Data evaluation	i	XXXXXXX
<u>Si Cells</u>		
Efficiency improvement	j	XXXXXXXXXXXXX
Radiation resistance development	k	XXXXXXXXXXXXXXXXXXXXXXXXXXX
Stability testing of experimental module	d	XXXXXXXXXX
Experimental module flight test	f	XXXXXXXXXXXXXXXX
Production cost analysis	l	XXXXX
Data evaluation	i	XXXXX

FIGURE 2.2.1

RECOMMENDED GBED PHOTOVOLTAIC CONVERSION PLAN (Continued)

	81 82 83 84 85 86
Blanket/Array	
Encapsulant development:	
Material development	xxxxxxxxxxxxxxxxxxxxxxx
Encapsulant testing	xxxxxxxxxxxxxxxxx
Preparation of encapsulant sample for flight testing	xxxxxxxxxxxxxxxxxxxxx
Interconnect design	xxxxxxxxxxxxxxxx
Submodule bussing analysis	xxxxxxxxxxxxxxxx
Preliminary blanket manufacturing concepts development	xxxxxxxxxxxxxxxxxxxxxxx
Concentrator reassessment	xxxxxxxxxxxxxxxx
Study of launch vehicle interactions	xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx
Analysis of array dynamics	xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx
Array-induced environment consideration	xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx
Advanced Concepts	
Demonstrate 25% (AMO) thin-film cascade solar cell	xxxxxxxxxxxxxxxxxxxxxxxxx
Investigate alternative systems to move toward 50% conversion efficiency goal (including split spectrum systems)	xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx

Notes (Figure 2.2.1):

a. Development goals: Cells on substrate material which is considered capable of becoming compatible, with base metal contacts (weldable, non-magnetic, co-planar). Cell stability tests to begin when 16% AMO efficiency reached

b. Cells with cover and substrate to be tested in GEO qualification test program, including thermal cycling, radiation damage/anneal, etc. Test contact integrity

c. Development target 1986: Cells of thickness 10 microns or less on compatible substrate, cell area 10 cm^2 or greater, efficiency 18% or greater, with base-metal contacts (weldable, non-magnetic, co-planar), with 16.2% 30 year GEO end-of-life capability, corresponding to 300 W/m^2 output

d. Experimental modules to contain a small group of interconnected cells, otherwise similar to b

e. Modest flight tests with experimental modules, to explore synergistic effects of GEO environment. To be flown piggy-back on suitable spacecraaft with primary non-SPS-related mission

f. To establish nature of radiation damage and annealing effects and to guide design of radiation resistant cells, both GaAs and Si

g. To identify potential barriers to attainment of cost-goals

h. To evaluate degree to which feasibility has been demonstrated

i. To demonstrate improvement from current 15% to 16% AMO efficiency by voltage increase in 50 micron thick cells of area 25 cm^2 or greater, base metal contacts (weldable, non-magnetic, co-planar)

j. To develop cells capable of 14.4% 30 year GEO end-of-life capability, with annealing at $300^{\circ}C$ or less (150 W/m^2 EOL output)

k. Definition of a strawman-process and analysis using SAMICS

The solar cell and blanket problems imposed by the requirements of SPS, and their potential impacts on the entire system design, were found to be extemely intricate. In light of the existing technology base with silicon solar cell production and application on spacecraft, and with successful power system development and operation in GEO, a large amount of background information exists which permits examination of many important interactions and problems.

As not all aspects of the preceding studies and the GBED plan relating to the SPS photovoltaic conversion system could be dealt with in this quick review, the effort was concentrated on the more obvious points of potentially substantial impact. In many aspects the GBED program, as defined previously, adequately covered the required development. Those aspects will generally not be discussed here.

2.3.1 Resource Requirements

Based on a variety of studies supported by the DOE terrestrial photovoltaic program and its SPS program, it was concluded that the availability of gallium in the 1990-2000 time period does not appear to be a critical issue for SPS development utilizing GaAs solar cells. The gallium is contained in bauxite and is recovered from slag resulting from aluminum production. Currently, 40% of its gallium content is extracted from the slag, but Alcoa claims that it can develop the technology to extract 80%. The conclusion is based on the amount of gallium needed for the production of thin film GaAs cells for SPS, under the assumption that only thin film cells would be appropriate for SPS, and that SPS would be the primary user of such cells. Although the availability of cost-effective Ga may be in question and may require development of new recovery methods, it is not believed that this is a GBED related issue. It is a matter to be studied thereafter.

There is a definite need to develop suitable contact metallization for both candidate photovoltaic devices. Present cell designs require gold or silver in quantities so large that SPS-required production might well exceed the metal production. In addition, strategic metals

such as Pt, Pd, and Cr are used in some designs. The use of alternate metals is thus necessary, also in view of the escalating prices for these materials. For instance, 27 km^2 of conductor area in a thickness of 2 microns, if made from gold, would require 990 metric tons of that material which would cost over $20 billion at current prices. This thickness may not even be adequate for low resistance conductors on large area cells. Available low-cost metals, such as aluminum, copper, and tin, are possible candidates. Development of contact systems using these metals is in progress in the terrestrial photovoltaic conversion program (e.g., the LSA project). Although verification tests to ascertain life of these contacts have not been performed, non-solvable problems are not expected. Also, it does not appear that these non-noble metals will be in short supply.

Supply problems exist currently for specific chemical metalorganic compounds required for some of the newer GaAs cell fabrication processes. These problems are industry capacity problems rather than resource problems, and are expected to be of a temporary nature only. Thus there are apparently no critical issues related to the need for natural resources for the photovoltaic converters for SPS that would require analysis or solution in the GBED program, provided cell designs are adjusted properly.

2.3.2 Solar Blanket

The solar blanket issues are connected with the photovoltaic element, its interconnects, and the encapsulant, which is composed of the cell cover material and the blanket supporting element. The issues relate to the blanket design parameters, particularly the performance, the mass, and the operating life in the expected SPS GEO space environment. For the photovoltaic element, two alternatives are so far the principal candidates: a thin-film GaAs cell, and a thin single crystal silicon cell (Figs. 2.3.1 and 2.3.2).

PHOTOVOLTAIC ENERGY CONVERSION SUBSYSTEM

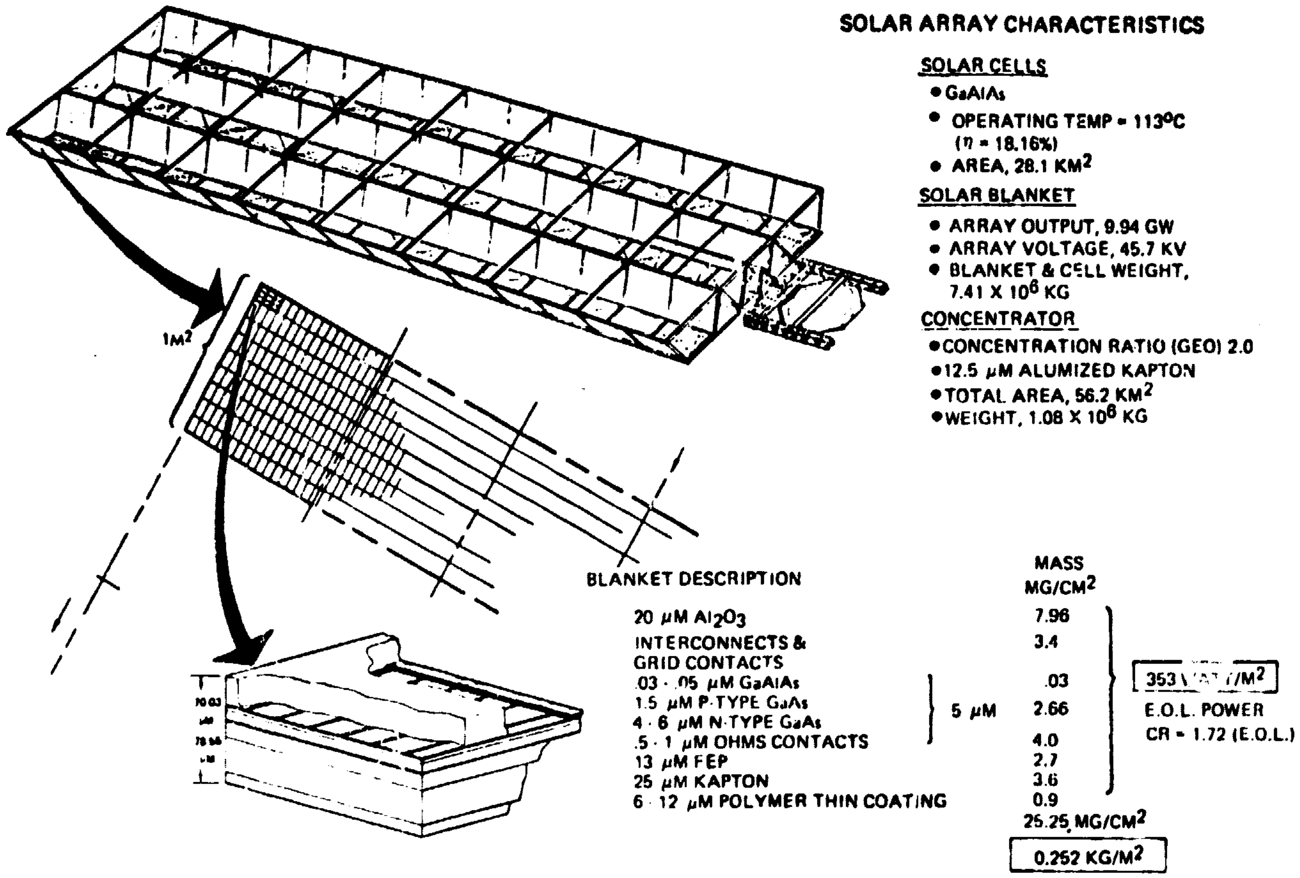


Figure 2.3.1 The Rockwell (GaAs) Blanket Design

Each 1 m^2 size panel is 70–80 microns thick, with an FEP-Kapton-Polymer sandwich layer as the mechanical substrate. The structural connection of the panels is not detailed.

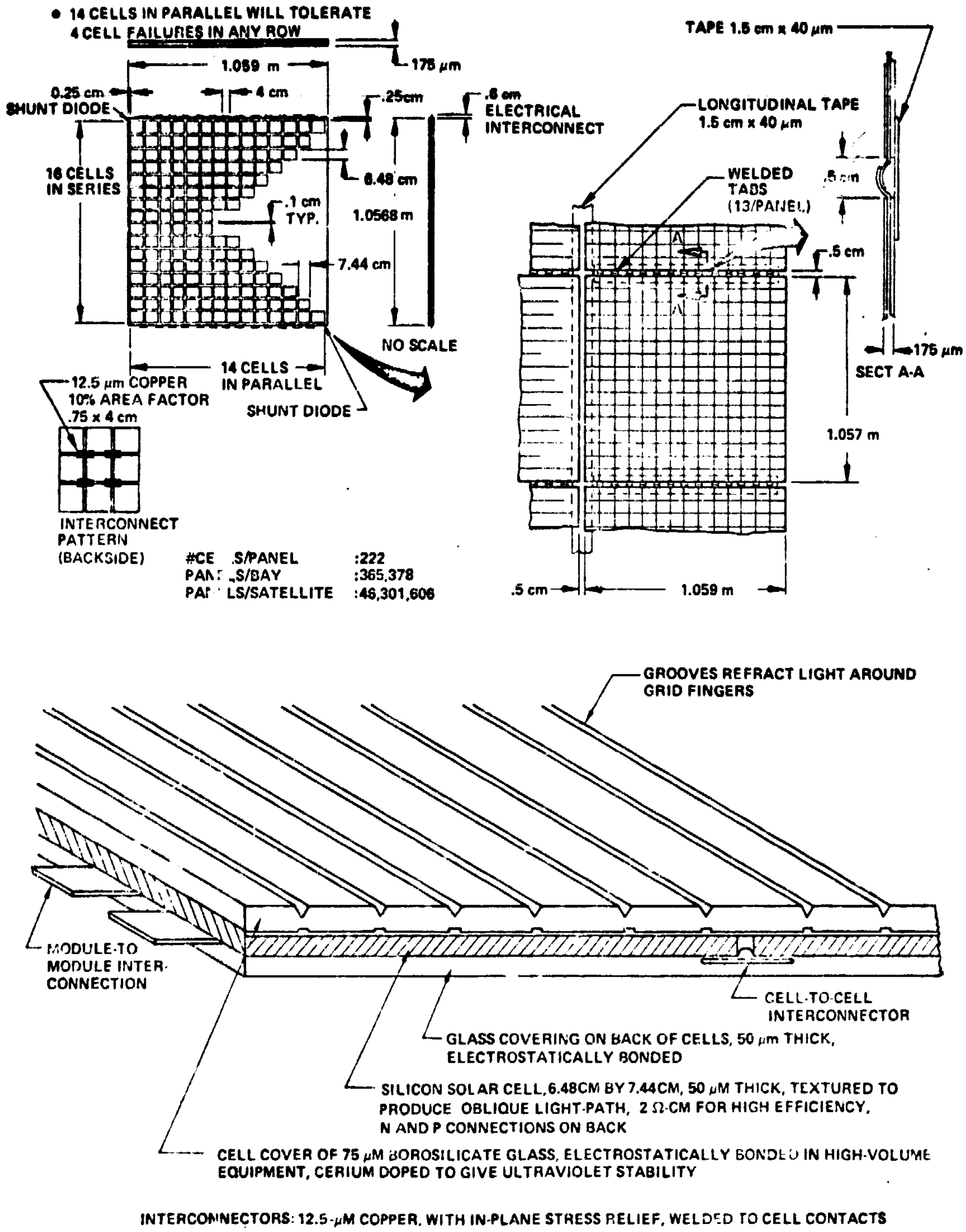


Figure 2.3.2 The Boeing (Si) Blanket Design

Note the 1.059 m x 1.057 m panel size, with 1.5 cm x 40 micron tape between panels providing the structural connection of the blanket. Panels are 175 microns thick glass-silicon-glass sandwiches.

In many respects, the parameters of performance, that is beginning-of-life (BOL) power output, of mass, and performance stability, which determines the useful operating life through the end-of-life (EOL) power output, are interrelated consequences of the solar cell and the blanket design, rather than readily separable, independent parameters. These parameters will, therefore, be discussed in conjunction.

Those issues which are believed critical and requiring resolution in the GBED program are identified. In many instances, the GBED program, as defined previously, adequately covered the required development.

2.3.2.1 The Supporting Element

A critical possibly "show-stopping" component of the photovoltaic system is the supporting element or encapsulant to which the active element, the photovoltaic cell is bonded (by deposition or by attachment). The encapsulation material has to provide the structural strength of the blanket and the shielding for the solar cells against the energetic particle radiation of space. Development of encapsulants with durability against bombardment by electrons and protons, ultraviolet radiation, and deep thermal cycling for a 30-year period is essential to the program. It is recommended that strong emphasis be given to the development of a suitable encapsulant material in the GBED program.

2.3.2.2 Gallium Arsenide Solar Cells

For the design of this type of cell, as it has been evolved for SPS, it is still necessary that the basic device technology be demonstrated. The goal of this GBED program should be to produce a GaAs based thin-film cell with 18% AMO efficiency with a thickness of 10 microns or less, and with an area of 10 cm^2 or more, fabricated on a thin, large area, potentially inexpensive substrate that is capable of meeting the SPS cost and weight goals. Relaxation of the current SPS efficiency goal of 20% for this cell structure is warranted in view of overall system

considerations. Although a very small GaAs thin-film cell with about 20% AMO efficiency has been demonstrated (Fig. 2.3.3), such cells have not yet been made on thin substrates that would allow the cell to meet the overall mass requirement of SPS. Since extension of even the more advanced of the present GaAs cell technologies to the designs required (or proposed) for the SPS may involve considerable further development, the reduced SPS cell efficiency goal cited above constitutes a reasonable recommendation for achievement by the end of the GBED program. However, it is recommended that sufficient emphasis and support be given to cell development so that, within two years, devices of 16% efficiency should incorporate all the critical elements that are expected for the 18% device. The intended uses of these lower performance cells are for various stability and lifetime verification tests, particularly radiation damage, environmental durability, and annealing characterization.

It is also recommended that development of contacts be conducted that use non-noble metals. Although trace amounts of noble metals may be necessary, the primary current-conducting component of the cell contacts should not contain expensive metals such as Au, Ag, Cr, Pt, or Pd, some of which may also involve the problem of limited resources. Some potential candidates include aluminum, tin, copper and nickel. However, the suitability of these contact metals under expected space conditions must still be demonstrated. These materials should be essentially non-magnetic and should be "weldable." The term weldable is not intended to be specific, and includes any suitable technology for interconnection other than soldering. Also, co-planar back contacts on the cells are envisioned. Top/bottom contacts cannot be ruled out, but they would require the development of an innovative cell-to-cell interconnection technology to meet the 30-year lifetime goal.

Appropriate cost studies should be conducted throughout the GBED program to ensure that the total array structure (cell, contacts, encapsulant, interconnects) is capable of meeting the SPS cost goals with suitable development and scale-up. Although extrapolations to expected technologies may be required, it is believed that the costs so determined can yield important program guidance.

A final recommendation for GaAs solar cell development is that an end-of-life (EOL) efficiency of 16.2% be demonstrated for the GaAs package for a 30 year equivalent combined radiation damage/environment exposure. The performance level selected allows a 10% loss in performance, which is a little more than double the SPS projection, but is considered more realistic at this time. In this connection, it should be noted that significant uncertainties still exist relative to the effects of the different solar cell structures, and particularly the effects of a combined radiation environment, as well as to the degree and repeatability of performance restoration by annealing, especially at relatively low temperatures. A fundamental research program aimed at understanding the radiation damage and annealing effects, to support the cell development effort, is therefore strongly recommended. It is anticipated that unexpected phenomena may appear during the ground-based environmental effects and life test programs, but these phenomena should be amenable to solution in development efforts to take place after GBED.

?.3.2.3 Silicon Solar Cells

It is recommended that a silicon solar cell can be demonstrated with 16% minimum efficiency (AMO), with 25 cm^2 or greater area, and 50 microns or less thickness. This performance level is about 8% below the SPS goal, but its achievement will require that an open-circuit voltage approaching the theoretical maximum be demonstrated. However, demonstration of the full 17.3% is not deemed necessary in the GBED program so long as the initial open-circuit voltage increase has been achieved. It is important to note that a variety of solar cell structures that produce more than 90% of the maximum expectable efficiency have been produced, but that the radiation sensitivity of these structures will not meet the SPS goal. Thus, a substantial development effort backed up by radiation testing will be required for these solar cells.

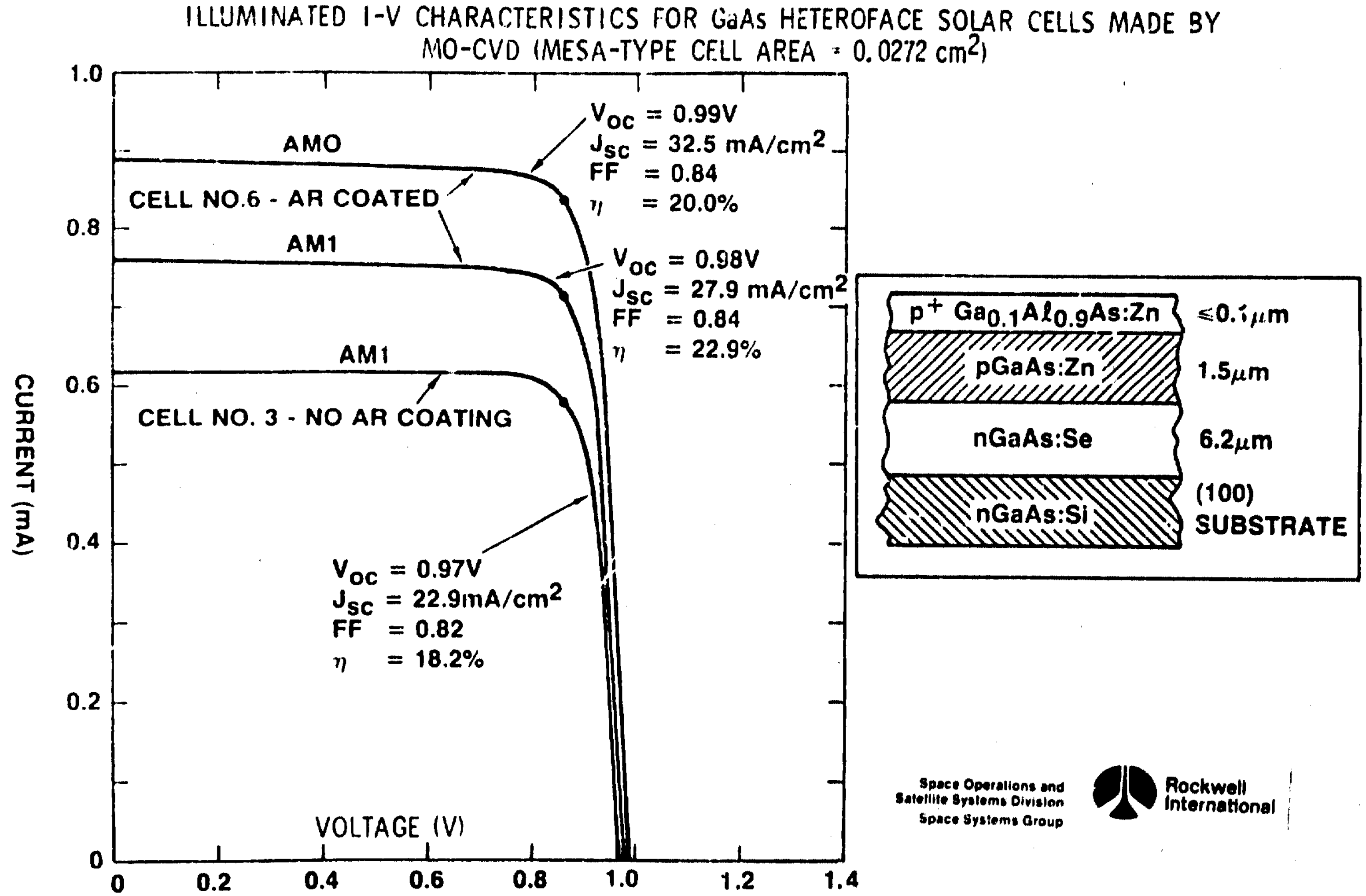


Figure 2.3.3 Characteristic and Structure of the Best GaAs Solar Cell

Prepared by thin-film methods so far. Note that the cell is of "mesa" configuration with 2.72 mm^2 area, and that the substrate is single crystal GaAs (Si-doped).

Devices capable of meeting the radiation resistance and/or annealing requirements can probably be demonstrated within three years from program start. However, the currently planned annealing at 500°C appears rather impractical from the viewpoint of solar cell and blanket life requirements. Temperatures near 200°C appear more manageable. The achievement of either adequate radiation resistance for a P_{EOL}/P_o of 0.9 or greater after 30 years in GEO, or of an adequate annealing capability in silicon at temperatures below 300°C, will require a fundamental research program aimed at understanding the effects occurring in silicon during and after particle irradiation and heat treatments which lead to damage and/or annealing in the various solar cell structures. It is strongly recommended that such concomitant basic research be carried out with adequate effort to support the development of either a radiation hard cell or one that can be annealed at temperatures well below 500°C.

It is also recommended that a program be initiated to demonstrate for silicon cells an EOL efficiency of 14.4% for the 30 year equivalent radiation damage/combined environment tests described in section 2.3.2.2. This level also represents a 10% decrease from the 16% efficiency previously expected as a rsult of GBED efforts, for the same reasons as outlined before.

Finally, a program is recommended to develop a weldable, non-magnetic, non-noble metal contact system capable of withstanding the annealing temperatures without failure. Although the development of non-noble contacts is in progress in the terrestrial photovoltaic program, the non-magnetic property is not required there, and the weldability is only of peripheral interest. Consequently, the contact system resulting from that program may not be suitable for SPS. It is also recommended that demonstration of blanket technology that is capable of meeting the SPS design goals with respect to W/kg, cost, and temperature (as required for annealing), and of withstanding the environmental conditions of GEO, be a part of the GBED program.

2.3.2.4 Manufacturing Process Development

Although a large-scale manufacturing capability will ultimately be needed for the SPS program, several orders of magnitude above present solar module production rates, the evolution

of new solar cell structures during the GBED phase would render premature any significant production process development effort, beyond fabrication in a laboratory-type pilot line of relatively small numbers of cells for the lifetesting program. However, to allow the feasibility evaluation at the end of the GBED phase, an evaluation of potential barriers to production within the SPS cost goals for the GaAs approach is recommended. For the silicon approach, which is based on a much more developed technology, and where many of the results of the cost reduction effort in the terrestrial program can be utilized, a strawman process sequence (paper design) should be laid out, and the manufacturing process evaluated according to the SAMICS methodology or, if needed, a variation of it.

2.3.2.5 Performance Stability

To meet the 30 year lifetime requirement, very good stability of the solar cells, the interconnects, the cell covers, and the supporting element is required in the operating environment (geosynchronous orbit). Four major influences of the environment are of concern:

(1) degradation caused by the energetic particle radiation which includes low-energy protons, medium-energy electrons and protons, and occasional large bursts of high-energy protons from solar flares

(2) degradation caused by the combined GEO environmental effects which include u.v. radiation, vacuum, and extreme temperature, in addition to the particle radiation

(3) possible degradation caused by the interdiffusion of different elements at their interfaces, particularly as the result of high operating or annealing temperatures

(4) material fatigue resulting from the extensive temperature cycling connected with the eclipses

As far as the solar cells are concerned, the degradation-causing particle flux mentioned in (1) can be reduced by the use of suitable shields (encapsulation), and its effect minimized by proper cell design. However, because the radiation dosage both during transfer from LEO to GEO, and in GEO during the operating life, is expected to produce significant unavoidable cell damage,

most SPS plans call for the use of on-site thermal annealing to restore the cell output. Since the radiation-resistance or recovery-by-annealing design goes substantially beyond previously attained levels, a basic research program should be conducted to elucidate the physical mechanisms involved and to change material or device properties to minimize radiation damage. This is discussed in more detail in sections 2.3.2.2 and 2.3.2.3.

Since it is difficult to predict the effects of the environmental factors, particularly the effects of different particle types and their fluence at the operating temperature, on various materials and cell designs, the GBED program must include extensive ground-based testing. This testing can be meaningful only when solar cell structures can be used which closely resemble those considered to be strong candidates for SPS use.

As some of the environmental factors of GEO (1 and 2 above) are not well defined and are time-varying (particularly the energy spectrum of the particle radiation), and as their synergistic effects as well as their long-time effects are difficult to simulate in ground-based tests, a simple but adequately instrumented on-orbit test should be planned to start during the last year of GBED as part of a space flight performed under another program. Since preparations for such a flight test are time consuming, they should start early in the GBED program.

The degradation effects described in (3) are expected to arise mainly from the long-term influence of elevated temperatures, which are either the on-orbit steady-state temperatures under solar irradiation without or with optical concentration, or the temperature needed for annealing. These effects can be evaluated in ground-based tests, and their impact controlled by careful selection of adjoining materials of construction of the cells and the blanket, or by the insertion of barrier materials.

The low mass of the blanket will cause very severe temperature cycling during eclipse periods, with consequent stress due to thermal expansion coefficient mismatches in the blanket structure. This leads to the material fatigue effects (4 above). The extent of these effects can be determined in ground-based thermal cycling tests, and the design, if needed, improved by selection of more suitable materials.

Suitable methods do not now exist for either the simulated, ground-based testing of the combined effects of the various components of the GEO environment, or for the accelerated testing to ascertain a 30 year operating life without gross overdesign. Therefore, an effort should be initiated to define, develop, and conduct an accelerated testing program to demonstrate that the array can perform satisfactorily for 30 years.

Other less important potential material or device degradation processes which will also need to be evaluated in ground-based tests include electro-migration caused by the high circulating currents and micrometeorite impacts.

2.4 Solar Blanket and Array Integration Issues

For the solar array review, it was assumed that the photovoltaic device which is yet to be defined in detail will be the driving element in the array design, and the effort was concentrated on identifying "SPS-unique" constraints as a basis of the review. It was also recognized that many of the considerations in array integration lead to new demands on the properties of the blanket components, which will subsequently have to be dealt with in the component development effort.

The presently used methods for space blanket formation employ relatively expensive materials, depend extensively on hand labor, and are based on discrete manufacturing operations. In the past ten years, space flight cells have increased in size from 1x2 cm to greater than 2x6 cm dimensions. This trend has been driven by assembly cost considerations: larger sized cells result in lower unit area assembly costs because of the reduction in the total number of handling operations. Thus, even larger area cells will be required for the SPS concept.

Since blankets of low mass, high performance, and long life will be needed to satisfy the SPS goals, it was found that every effort should be made to eliminate or modify blanket elements that appear to severely compromise the criteria established for an SPS blanket. In addition, any

candidate component of the blanket should be capable of being mass produced by automated assembly techniques.

In view of the significant developments during the last three years in silicon back surface reflector cells, split spectrum devices, and improved cost-effective cold mirrors, a complete re-evaluation of the methodology is indicated which leads to the selection of a preferred solar concentration ratio to be used in conjunction with a particular SPS photovoltaic blanket. These new developments warrant a re-examination, at the systems level, of the present conclusions reached in the SPS concepts study. Both low (less than 5) and high concentration (greater than 5) concepts should be evaluated in terms of system cost and mass, using conventional (Si and GaAs) as well as advanced (split spectrum, cascaded) solar cells. Such new studies could provide an even more optimistic perspective for the SPS with respect to performance and cost. This would then provide some additional technological "breathing room" for the concept.

2.4.1 Blanket Integration

A "strawman SPS blanket" was considered, based on encapsulating the welded submodules with a material, glass or organic, which would be capable of meeting the SPS environmental, manufacturing and performance requirements. This would mean a relatively thin layer (25 micrometers) of encapsulant which has low mass, can survive 30 years in geosynchronous orbit without significant degradation in its mechanical, optical and thermal properties, and which would lend itself to encapsulation techniques that would not compromise the other components of the blanket. The development of such an encapsulant is of critical importance in order to demonstrate blankets of specific power high enough to satisfy the goals of the SPS program, and will be needed regardless of the cell (GaAs, Si, etc.) that will ultimately be used.

Because of the scale of the SPS, integrated techniques for producing blanket submodules capable of delivering perhaps hundreds of watts must evolve. Adhesives which are now used for bonding circuits to the substrate and protective covers to the cells will likely need to be eliminated because of their relatively high mass in the thin blanket structure and because of their

inherent environmental limitations. The encapsulants may not now exist which could satisfy the basic materials properties required for SPS: low mass, insensitivity to thermal shock and high temperature excursions, resistance to the synergistic effects of the space radiation environment (u.v., electrons, and protons), and capability of high density blanket storage and transport.

In order to be able to assess feasibility by the end of GBED, the technical means which will permit approaching the specific-power, lifetime, and cost goals of the SPS concept in this century should be known by 1986. It will thus be necessary to develop a space-worthy, SPS compatible encapsulation system during GBED. Such a system directly impacts the main requirements for the SPS array, but has also numerous advantages for all other space systems. An appropriate encapsulant allows the consideration of forming entire submodules in a single operation, thus increasing manufacturing throughput and reducing cost. Developments along these lines for terrestrial photovoltaics have already clearly demonstrated the gains in manufacturing volume and cost reduction that may be expected in the case of the SPS array.

The development of such an encapsulation system would allow the elimination of adhesives. Recent studies have shown that as the specific power of the cell approaches 1000 W/kg, which would be the case for either GaAs or silicon, the mass of adhesive used per unit becomes the limiting factor in determining the specific power of the blanket. Efforts to further reduce adhesive thickness or coverage would raise serious questions concerning array reliability. One of the main causes of interconnect fatigue during extended deep thermal cycles is based on the interactions that take place between the interconnect and the adhesive at low temperatures, a condition that will be encountered by the SPS array in thousands of very deep thermal cycles. The elimination of these interactions would greatly enhance the survivability of the array, and improve the prospects for a 30 year operating lifetime.

There is an obvious need for work addressing both interconnect and submodule bus designs. These array components will have a significant influence on the ultimate cost and performance of the system. The main problem that can be presently identified is the trade-off that must be made between interconnect and bus mass and the required electrical performance of the array

submodules. A cursory examination of the interconnect technology has indicated that there are obvious problems when relatively large cells and submodules are being considered. The goal should be to considerably reduce interconnect mass while handling significantly larger amounts of power than in present spacecraft, and to simultaneously be able to survive at least 3000 deep thermal cycles with in-plane-stress-relieved interconnects. This will require a great deal of further study. Determination of the required dimensions and materials for the interconnects and busses as a function of cell and submodule size would be a logical starting point, and should be carried out at the beginning of the GBED program. Interconnecting the cells and modules by some form of welding should, however, not present a major problem, and will facilitate meeting a number of the SPS design constraints.

Another concern is the ability to manufacture such a blanket in an economic fashion. The geometry of the blanket submodules, very thin and very large, requires new approaches and innovative machinery for fabricating these blankets. This part of the program cannot be further addressed until a better understanding of the final cell and submodule configuration is developed. Nevertheless, a preliminary assessment of techniques for economically manufacturing the array should begin. This is required in order to provide some credible estimates of the SPS system cost by the 1986 assessment date. Such data may be paced by the activities associated with encapsulant development. However, such work could begin within two years after initiation of the encapsulant effort.

As in the blanket detail review, it was found here that the GBED phase needs to begin some limited space flight test experiments. Such efforts could be shuttle launched or "piggy-backed" on existing spacecraft. The recommendation for space experiments is based on the fact that it is not possible to develop the necessary ground-based facilities to provide the synergistic environment of a geosynchronous orbit. The availability of actual space data in order to realistically evaluate the technology feasibility for SPS is essential. The test experiments should be designed to obtain definitive data on a particular aspect of any technology being evaluated. We cannot

presently see the need for dedicated, and therefore more costly, spacecraft for this part of the effort.

2.4.2 Array Integration

Although it is not a present critical requirement for SPS viability, the lack of information concerning the various subsystems interfaces offers a potential for ultimately delaying or compromising the SPS effort.

While the array structure was not addressed in this workshop, problems associated with packing, launching, and deploying very large, low mass arrays became immediately apparent. It is recommended that every effort be made to identify the properties of the proposed launch vehicles at an early time so that the preliminary array design can be configured for a match to the launch vehicle. For example, the acoustic environment of the launch vehicle dictates the packaging requirements for the blanket or array, and the damping material required may well exceed in mass and/or volume those of the blanket to be transported. This environment must therefore be bounded as soon as possible, so that the array may be configured to survive the launch. In addition, the volume constraints of the vehicle must be known sufficiently to allow launch configuration design for the most efficient utilization of lift capacity.

The size of an SPS array is such that presently available methods for predicting its dynamic behavior in orbit are not adequate. The question of how the array is to be oriented must be considered in some detail at this stage of the program to ascertain the mechanical requirements on the array and blanket resulting from the orientation maneuvers. Also, the influence of subtle changes with age in the thermal and mechanical properties of the array and the associated concentrator system must be addressed in at least a preliminary fashion during the next few years. All this information must be fed back to the array design effort in order to avoid a baseline design that is inherently incapable of operating at the required performance level for the required time in orbit.

A set of "SPS unique" problems that need adequate definition are those associated with the environment that the SPS array itself will induce, simply because of its size and the power being distributed over its area. Some obvious areas that must be addressed are the plasma effects that might result from the high operating voltages, potential electromagnetic pulse effects that could result from transients to and from occultation, magnetic dipole effects from the high bus currents that could severely change the dynamics of the array, and safety considerations during array repair. It was found that the blanket needs to be designed as an easily exchangeable modular item to facilitate repair of the array. Such information on the potential effects the array may induce in itself must be made available within the next few years in order to provide some clues as to the proper design approach needed for the SPS array.

2.5 Advanced Concepts

It is recommended that the GBED program include investigation of advanced concepts that offer the potential of significant advances in performance, mass and/or cost of the photovoltaic energy conversion system over the "mainstream" concepts and designs. At least some of these investigations should commence at the start of the GBED program, and some advanced concept activity should be in progress throughout the six-year GBED program.

With the intention being of allowing new developments in existing technologies, as well as totally new concepts evolving during the GBED period to provide a major portion of the Advanced Concepts activity, specific advanced concepts nave not been included in this recommendation with one exception.

The one specific advanced concept recommended by the group for further immediate development is the cascaded or tandem multiple-bandgap solar cell -- a concept already being investigated in several materials systems under Air Force sponsorship for various space power supply requirements, and under DOE/SERI sponsorship for high-efficiency terrestrial concentrator cell applications. The materials now under investigation involve GaAs or related compounds as a

component in the cells required, but there are few, if any, restrictions placed on the substrate material or its thickness (mass), or on its cost.

It is recommended that development of the cascaded cell technology be extended with specific orientation for the SPS, which includes the added specification of a limited substrate or encapsulant mass. It is recommended that the aim of this development be demonstration, in experimental cascaded thin-films cells, of the achievement of 25% efficiency at AMO within the GBED program period, and of the potential for achievement of 35% efficiency at AMO in the same or separate development. The latter efficiency figure need not be demonstrated within the six-year GBED program, but may result from suitable experimental data and appropriate extrapolations.

It is also recommended that other advanced concepts -- which might include, but not be limited to, such devices as split-spectrum systems, thermo-photovoltaic converters, and combined thermal-and-photovoltaic systems -- be investigated and, if so indicated, developed for the purpose of achieving conversion efficiencies approaching 50%. It is recognized that such investigations may be of a "high-risk" nature, but some activity of that type is required to properly carry out the intended mission of the GBED program.

3. SOLAR THERMAL CONVERSION SYSTEMS

The thermal engine concept is a viable candidate for solar energy conversion in the SPS. The performance estimates of the solar thermal conversion approach, in terms of economics and mass as given by the previous Boeing and Rockwell studies, are not substantially different from those projected for the photovoltaic reference system. However, all energy conversion concepts currently being considered, whether photovoltaic or solar thermal, cannot achieve the SPS goals for cost and weight. For both approaches advances in technology are required and among the competitive systems, performance differences are largely contingent upon results assumed for technology programs not yet performed. Therefore, within our present knowledge, the photovoltaic and solar thermal systems are competitive in weight and cost. In addition, there are important comparative advantages that appear to be inherent in the solar-thermal approach. For example:

- Solar-thermal equipment is relatively insensitive to radiation effects, both during transport from LEO and GEO and during 30 years' exposure to the GEO environment
- Gravity gradient compensation may be accomplished through mass distribution thereby reducing the need for stationkeeping with thruster propellant
- The power conditioning of generated electricity for the microwave transmitter will be significantly easier using the solar-thermal approach
- The production of the 40-200 turbine generators required for one SPS appears to be a reasonable annual output for existing industry

There is considerable concern at present that the current emphasis on the photovoltaic approach to the exclusion of promising solar-thermal options may result in an inadequate examination of the solar-thermal approaches. It is therefore recommended that renewed attention be given to a solar-thermal study program which will investigate new systems configurations that take advantage of recent advances in thermal engine technology.

The following sections provide:

- A critique of the results obtained in previous solar-thermal studies
- A discussion of light weight structures which addresses structural requirements for the solar-thermal systems goals for performance and economics along with comments on the present level of advanced space structure technology
- A discussion of advanced thermal engine systems along with improvements which can be reasonably expected from additional studies
- A discussion of advanced radiator concepts and their favorable impact on the solar-thermal approach
- Proposed programs for GBED which permit further evaluation of the solar-thermal approach
- Concluding remarks

3.1 Critique of Contractors' Results

The studies that have been performed to date in the solar thermal conversion area have been broad in scope and have included the systems listed in Table 3.1.1. Although numerous systems have been examined, the assumptions that were used in the analysis of the solar thermal systems were generally conservative. If reasonable projections of future technology advances are taken into consideration, as they were in the case of the photovoltaic systems, a solar thermal system may have a considerably lower mass than that which was projected by the earlier studies. This point will be illustrated with respect to the Brayton system which was one of the solar thermal systems examined.

Table 3.1.1

Thermal Energy Conversion Systems Reviewed for This Report

I. Thermal-Solar

1. Brayton
2. Potassium Rankine
3. Cesium/Steam Combined Cycle (Rankine)
4. Organic Rankine
5. Thermionic (Including TI/Brayton Combined)

II. Solar Concentrators

1. Parabolic (Including Compound Parabolic Conc.)
2. Faceted
3. Casagranian
4. Planar (CR = 2 to 8)
5. Inflated

III. Thermal-Nuclear

1. Rotating Particle Bed Reactor
2. Molten Salt Breeder Reactor (MSBR)
3. Uranium Hexaflouride (UF)
4. Conversion Cycles (Brayton, Rankine, Thermionic)
   - LMFBR
   - GCFR
   - Ceramic pebble-bed reactor
   - Gas-core reactor
   - Fusion reactor

IV. Radiators

1. Heat Pipe
2. Fin-Tube, Liquid
3. Fin-Tube, Vapor/Gas

3.1.1 Thermal Systems' Development Issues

The earlier studies reviewed by this panel examined the important problems associated with space thermal power systems. While these studies tended to differ among themselves, by and large they did address the major issues associated with solar thermal systems listed in Table 3.1.1 to define areas which require further study in order that a real assessment of the comparative developmental risks between solar thermal and solar photovoltaic systems can be made.

Both photovoltaic (silicon or gallium arsenide) and thermal cycle (Brayton or Rankine) appear to be technically feasible solar energy conversion methods; however, photovoltaic systems may have lower mass than solar Brayton and Rankine cycle system concepts, the costs of photovoltaic systems may be less than thermal cycle systems, and photovoltaic systems may have higher reliability potential than thermal cycle systems because of the inherent redundancy features of photovoltaic array design, passive system characteristics, and lack of an active cooling system.

The space construction cost appeared to be higher for thermal engine systems than photovoltaic systems because a larger crew size and larger construction facility could be required and the packaging space transportation costs could be higher.

The solar Brayton cycle system with helium working fluid may have the following disadvantages:

- Large, heavy radiator system, including the requirement for leak-tight fluid joints
- Difficult requirements for efficiently constructing solar concentrators and radiators
- Low packaging density components, which increase space transportation costs

The solar potassium Rankine cycle system may have the following disadvantages:

- Difficult requirements for efficiently constructing solar concentrators and radiators
- High temperature, vapor-phase radiator system requiring leak-tight joints and seals, including adequate meteoroid impact protection for tubes
- Low packaging density components, which increases space transportation costs

Maintenance considerations for the cesium/steam Rankine dual-cycle system may be excessive. The complexity associated with repair and replacement of a large number of massive components and potential problems of fluid system leaking may render this concept unattractive for further consideration.

Thermionic conversion systems examined resulted in a satellite mass 50-100% greater than with other thermal cycle systems, and 2 to 5 times greater than photovoltaic systems. As a result, the thermionic systems have a higher projected cost than other candidate systems because of high transportation costs. However, should more efficient thermionic diodes be developed, satellite mass would be greatly reduced.

Space nuclear reactor systems utilizing rotating particle bed, molten salt and uranium hexafluoride breeder reactor system with thermal cycle (Brayton, Rankine, and thermionic) offer the advantage of compactness relative to solar powered systems. It should be noted that little effort was devoted to the nuclear system options, and the mass calculations were analagous to taking off-the-shelf terrestrial photovoltaic panels (weighing about 200 kg/kw) and using this information to determine photovoltaic SPS system mass. Also, significant safety and environmental questions exist and were not studied.

While the systems definition studies indicated a cost advantage for photovoltaic systems over the thermal system utilizing the ground rules of these studies, it should be emphasized that these differences are nonetheless small. By and large this advantage stems from satellite mass differences which in turn affect transportation costs.

The cost advantage of photovoltaic systems is very sensitive to solar array blanket cost and weight when compared to solar thermal systems. Thus a small difference in the actual achieved efficiency of the type of solar cells which must be developed for space applications could change this result dramatically. To illustrate this point, Fig. 3.1.1 shows a cross trade-off between the

potassium Rankine cycles and the projected performance of a space-worthy silicon photovoltaic system. At the projected solar blanket cost, the silicon system appears to have a 5-10% cost advantage which could easily be lost unless the project efficiency is fully achieved.

3.1.2 Brayton Cycle Concepts

A schematic diagram of the cl ed Brayton cycle system shown in Fig. 3.1.1 illustrates the fundamental elements of the Brayton cycle SPS. The solar concentrator reflects and focuses concentrated sunlight into the cavity absorber aperture. The cavity absorber is an insulated shell with heat exchanger tubing. Helium gas flowing through this tubing is heated to the turbine inlet temperature. The hot helium expands through the turbine doing the work of turning the compressor and the electrical generator. Residual heat in the turbine exit gas is used to preheat compressor output gas before final heating in the cavity absorber. This heat transfer is accomplished in the recuperator, which is a gas-to-gas heat exchanger. The minimum gas temperature occurs at the exit of the cooler, which is a gas-to-liquid heat exchanger interfacing the helium loop to the radiator system. Waste heat is rejected to space by a radiator.

The total mass of the satellite, not including growth allowance, is 76,619 metric tons for a 10 GW system. Fig. 3.1.2 shows a mass statement for the Brayton SPS concept. Note that the radiator constitutes almost 40% of the satellite mass.

Reference(s)

SPS System Definition Study, NASA Contract NAS 9-15196, Boeing Aerospace Company, Report/Number/Date.

1. System Requirements and Energy Conversion Options, Part I, Volume 2/D180-20689-2/July 29, 1977.
2. SPS Satellite Systems, Part II, Volume III/D180-22876-3/December 1977.

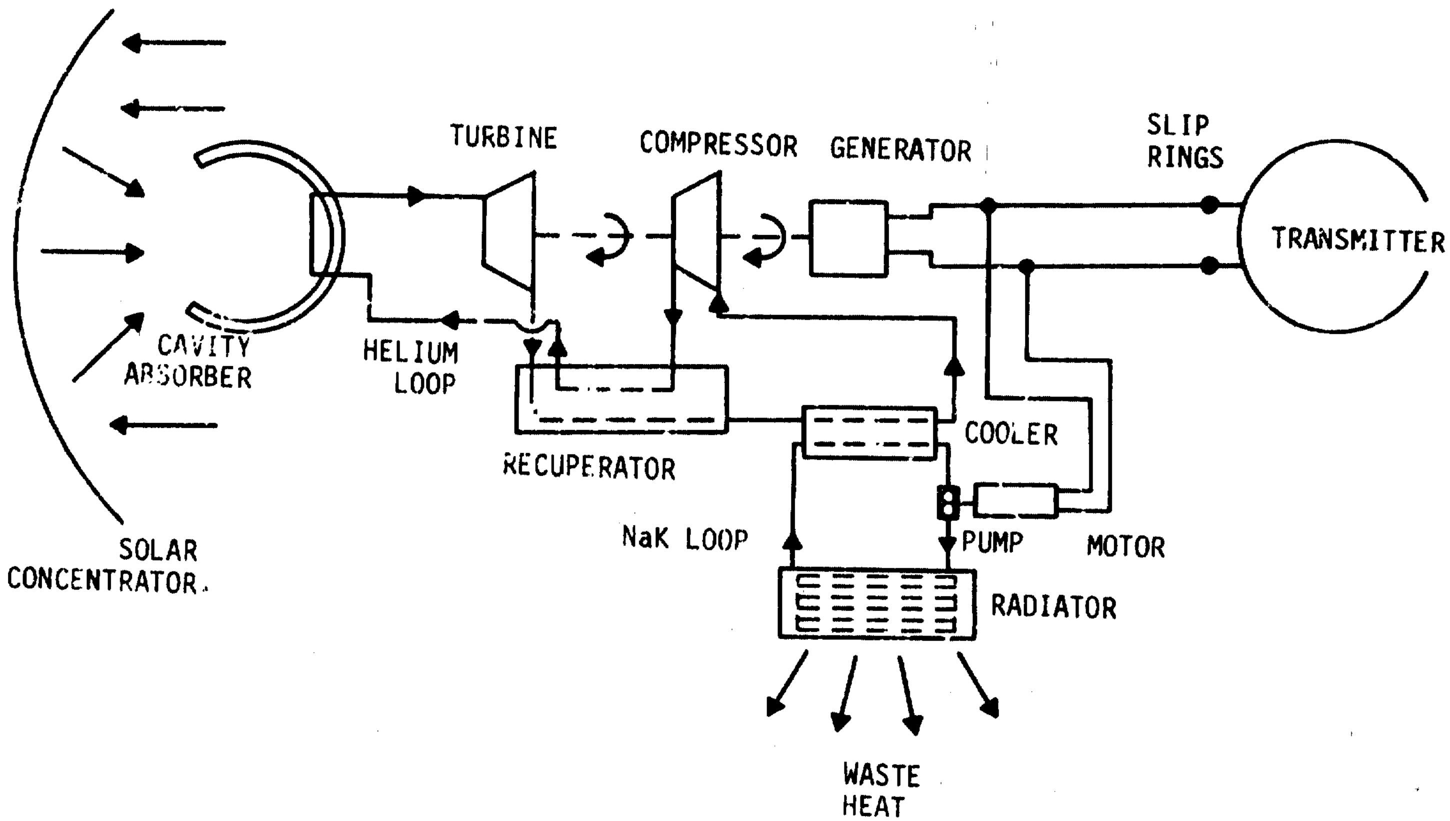
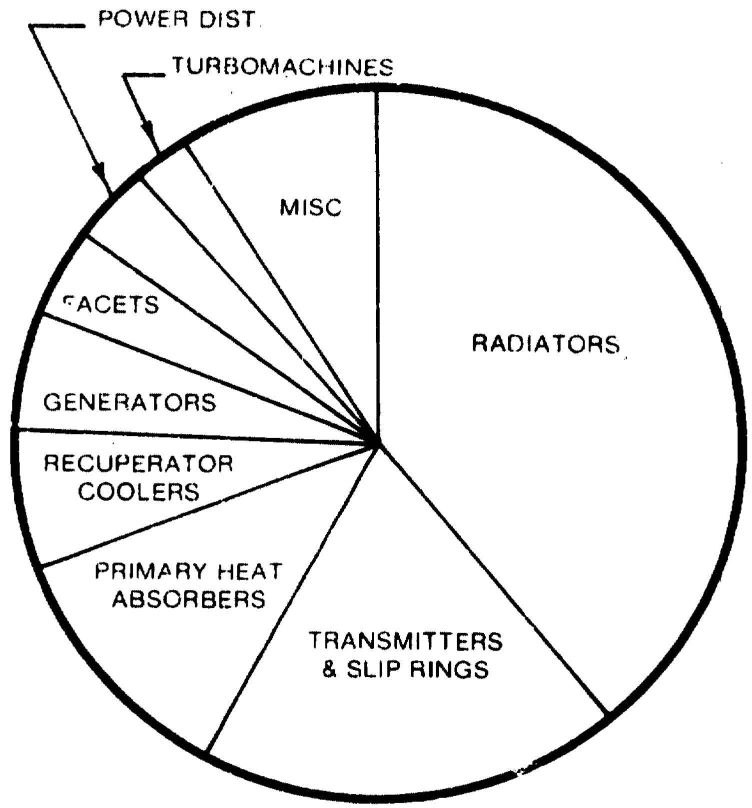


Figure 3.1.1 Brayton Cycle

ITEM	10^6Kg
RADIATOR SYSTEM	30 951
TRANSMITTERS & SLIP RINGS	15 370
PRIMARY HEAT ABSORBER	9 070
RECUPERATOR/COOLERS	4 860
GENERATORS	4 320
FACETS, INCLUDING STRUCTURE *	4 200
POWER DISTRIBUTION	3 370
STRUCTURE	2 730
TURBOMACHINES	1 950
CAVITY ASSEMBLIES	1 420
GENERATOR COOLING	0 620
SWITCH GEAR	0 400
ATTITUDE CONTROL/STATION KEEPING	0 340
LIGHT SHIELD ASSEMBLIES	0 200
ONE YEAR's CONSUMABLES	0 200
BRAYTON SPS	79 601

* STRUCTURE SYSTEM ASSOCIATED WITH PLASTIC FILM TENSIONING



MASS DISTRIBUTION
(10 GW SYSTEM)

Figure 3.1.2 Brayton Cycle Mass Statement

The major assumptions and tables involved in the design of the Brayton SPS described above are as follows:

1. Turbine inlet temperature - 1610°K (2438°F) - subsequently reduced to 1242°K (1776°F) to utilize near-term materials technology; i.e., refractory alloys in lieu of ceramics
2. Cycle temperature ratio - 0.25 - subsequently raised to 0.41 for minimum radiator area
3. Energy conversion efficiency - 45% - subsequently reduced to 21% as a result of the above temperature changes
4. Generator efficiency - 98.5%
5. Cavity absorber efficiency - 70.2%
6. Solar concentrator efficiency - 55.1%
7. Reflector film reflectivity - 0.87 BOL, 0.625 EOL
8. Radiator inlet/exit temperatures - 597K/395K
9. Faceted (heliostat)-type solar collector/concentrator

The major tradeoff studies that have been performed leading to the concept described are as follows:

1. Turbine inlet temperature and cycle temperature ratio versus system efficiency/radiator area/system mass (Fig. 3.1.3). Initial concepts with 1610°K (2438°F) turbine inlet temperature yielded a satellite mass of 79,610 metric tons; however, this concept required advanced materials technology (ceramics). Reducing the turbine inlet temperature decreases system efficiency thereby increasing satellite size (collector area) and mass. At 1242°K (1776°F) and a cycle temperature ratio of 0.41 (minimum working fluid temperature divided by maximum working fluid

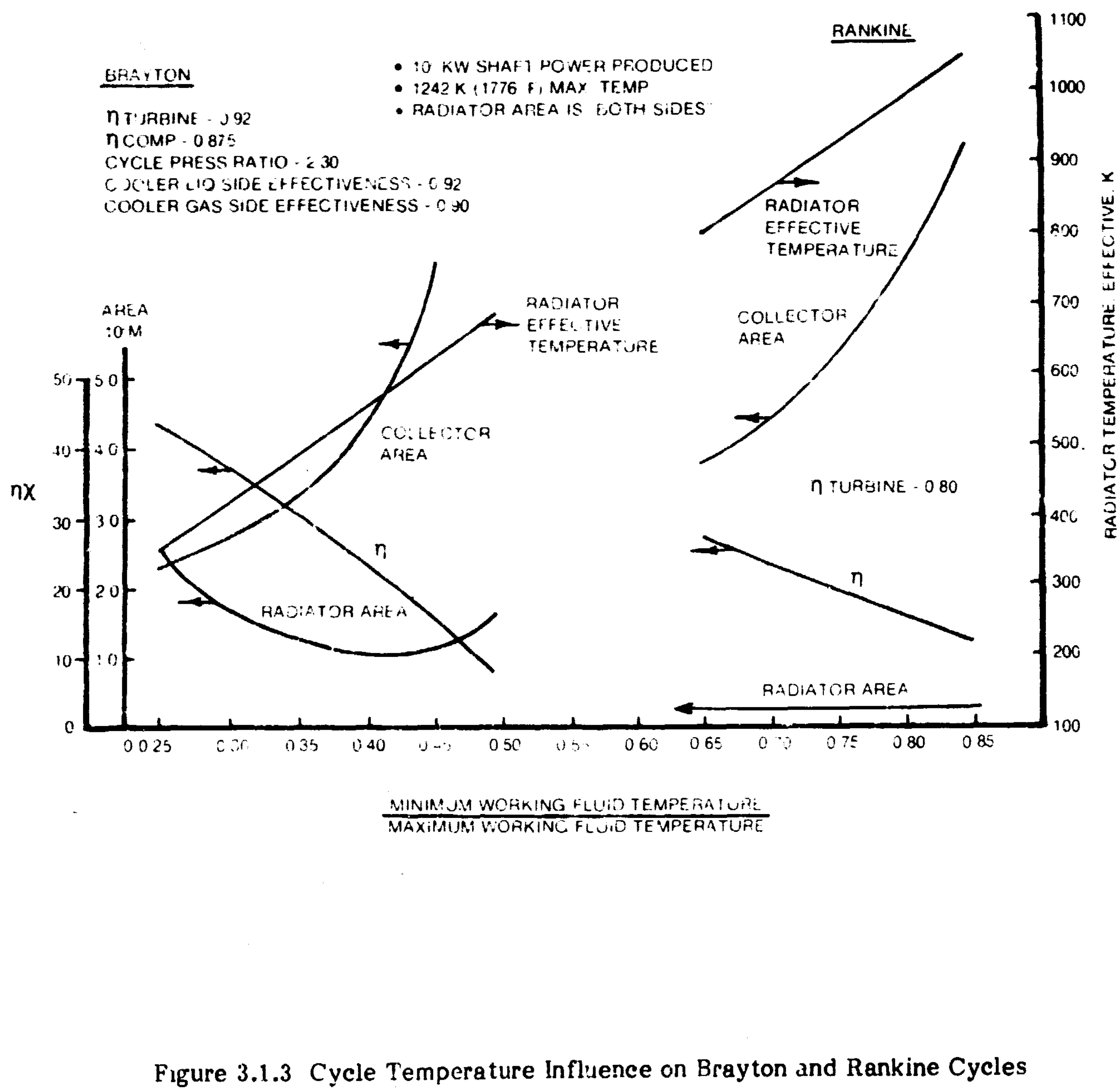


Figure 3.1.3 Cycle Temperature Influence on Brayton and Rankine Cycles

temperature) the cycle efficiency is 21% but the radiator area is minimized (see Table 3.1.2). The 1242°K turbine inlet temperature design was selected for final system comparison studies

2. Space radiator design tradeoffs: gas (working fluid) radiator; pumped liquid metal with/without heatpipes; alternate mass folding concepts; meteoroid protection criteria. The preferred concept based on mass considerations is a pumped liquid metal (NaK) system which transports waste heat from the thermodynamic Brayton cycle engines to a water heatpipe radiator system

3. Alternate construction techniques/design approaches to facilitate construction: free form, facilitized, and extrusion

4. Solar concentrator/absorber trades:
   - Number of facets vs. efficiency
   - Geometric concentration ratio
   - Cavity receiver efficiency vs. mass

The Brayton cycle SPS concept has been compared with a number of other thermal cycle systems as well as with photovoltaic systems. Table 3.1.2 shows a comparison of the Brayton system with Rankine cycle (potassium and cesium/water combined) and thermionics. The Brayton and potassium Rankine systems of Table 3.1.2 were designed within the context of the same system definition study (Contract NAS 9-15196, Boeing Aerospace). The cesium/water 5 GW Rankine system design was produced by Rockwell International under Contract NAS 8-32475.

System masses, areas, etc. were simply doubled for direct comparison with the 10 GW Brayton system. The thermionic system of Table 3.1.2 resulted from an earlier study by Boeing under contract NAS 8-31628 to the Marshall Space Flight Center.

	BRAYTON	K-RANKINE	CESIUM/WATER RANKINE	THERMIONIC
SYSTEM MASS, 10^6 KG	102	86	85	197
RADIATOR AREA, KM^2	6.8	1.8	2.2	1.2
RADIATOR MEAN OPR. TEMP., °K, (°F)	360 (189)	930 (1215)	463 (400)	900 (1160)
PEAK CYCLE OPR. TEMP., °K (°F)	1242 (1776)	1242 (1776)	1311 (1900)	1800 (2780)
DESIGN LIFE, YEARS	30	30	30	30
HIGH TEMPERATURE MATERIALS REQUIRED	REFRACTORY Hx; TURBINE	REFRACTORY Hx; TURBINE	REFRACTORY BOILER; TURBINE	REFRACTORY METAL CAVITY, ABSORBER, DIODES
RADIATOR FLUID(S)	NaK – LIQUID	K-VAPOR - Na HEAT PIPE	STEAM/WATER (VAPOR/LIQUID)	Na - HEAT PIPE (VAPOR LIQUID)
DEVELOPMENT RISKS	MEDIUM - LARGE TECH. BASE IN MOBILE & STATIONARY	MID-TO-HIGH TOXIC, CORROSIVE WORKING FLUIDS	HIGH-CORROSIVE WORKING FLUIDS; COMPLEX	HIGH-LIMITED TECHNOLOGY BASE
KEY DEVELOPMENTAL PROBLEMS	LARGE RADIATOR CONST. & OPER.	CORROSION, EROSION TWO-PHASE FLOW IN O-G; BEARINGS & SEALS; K-LEAKAGE	CORROSION, EROSION, TWO-PHASE; LEAKAGE; INTEGRATION	EFFICIENT, LONG-LIFE CESIUM DIODE DEVELOPMENT; SYSTEM WEIGHT COMPLEXITY; LOW VOLTAGE SOURCE

Table 3.1.2 Thermal Cycle Trade Study

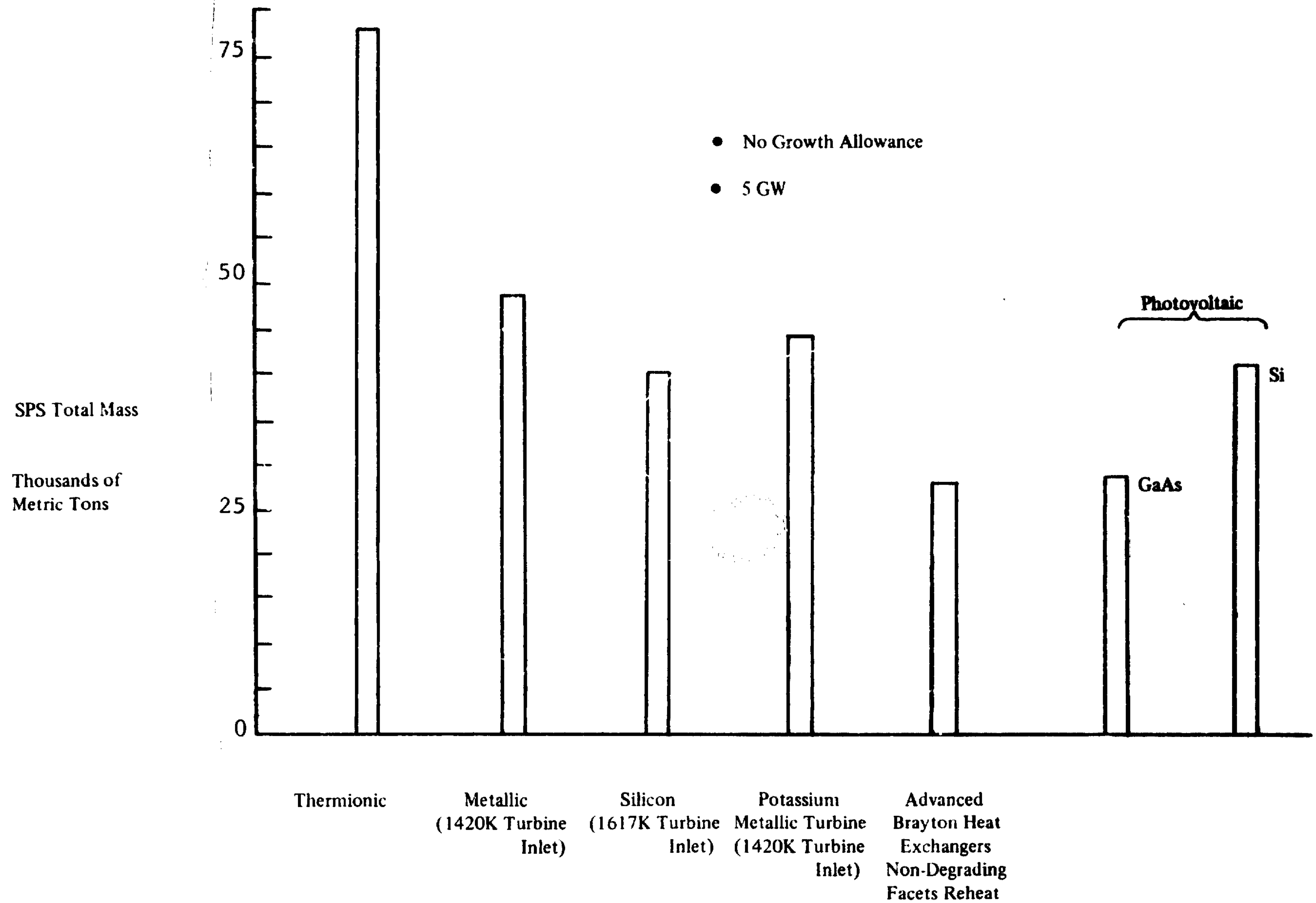


Figure 3.1.4 SPS Mass Comparisons

The major conclusion/results of this study with respect to a Brayton cycle SPS are as follows:

1. The mass of the Brayton cycle SPS was 79,610 metric tons including the microwave system (but with no growth allowance) at a turbine inlet temperature of 1610°K (2438°F) and a cycle temperature ratio of 0.25. The portion of the mass attributable to solar energy collection and conversion was 63,290 metric tons or about 4 kg/kw orbital power output. This design requires use of emerging technology ceramic components. Reduction of the turbine inlet temperature to refractory technology 1242°K (1776°F) and selecting a 0.41 cycle temperature ratio for minimum radiator area results in an increase of satellite mass to 102,000 metric tons
2. Radiator mass is the dominant element of the total satellite mass (see Fig. 3.1.3). Therefore, any advances in radiator technology which result in lighter radiators can have a major impact on SPS thermal conversion system performance characteristics

The solar Brayton cycle system is presently considered only a backup candidate to the primary silicon and gallium arsenide photovoltaic options. As a result, this system has been de-emphasized in study efforts. Its primary disadvantages (relative to photovoltaic) have been said to be higher satellite mass and more complex space construction operations. Technology improvements that would make the Brayton system more competitive include lighter weight radiator systems (with development of leaktight fluid joints) and high temperature materials (ceramics for example) to permit turbine inlet temperatures in the range of 1600 $^{\circ}$K or higher. These improvements would result in overall cycle efficiencies of 45% or more, greatly reducing satellite size and mass.

With respect to the nine assumptions listed for the previous Brayton SPS study, it should be noted that these were not uniformly applied to all systems. For example, the assumption of 0.625 EOL reflector film reflectivity that was used in the analysis of the Brayton system was

significantly lower than that that was used in the analysis of the gallium arsenide photovoltaic system. Similarly, the assumption of a 1242^{o}K turbine inlet temperature leads to a high mas system whereas if a higher inlet temperature (1750^{o}K) is assumed the mass can much less than that of the silicon photovoltaic system. A complementary development program in the ceramics area is presntly underway. Using the higher turbine inlet temperature, a solar thermal mass comparison is shown in Figure 3.1.4. A summary of some of the solar thermal system results is shown in Table 3.1.2.

3.2 Collector Structures for Solar Construction

The collection of the large amounts of solar radiation needed for SPS obviously requires very large areas. The high concentration ratios needed for efficient thermal power conversion requires that the surface areas be oriented accurately. The economics of the systems require that the collectors be fabricated at low cost per unit area and have reasonably low mass.

Since 1978, concerted efforts have been devoted to the problem of manipulating sunlight in space, in connection with the Halley Comet Rendevous Solar Sails Studies. An important conclusion of that study was that the technology of thin polymer films is far enough advanced as to allow the fabrication of kilometer-sized areas for launch in the early 1980's. The baseline film system consisted of 2 micron thick Kapton film, coated with vacuum-deposited aluminum on the reflector surface. Several means of producing the thin films were found to be available, including casting, chemical etching, and electrodeposition, as well as the standard approach of stretch forming, which was demonstrated during a special run at duPont's commercial Kapton facility.

The mass per unit area of the baseline reflector film is about 4 g/m^2 and the cost in the quantities needed for SPS would certainly be less than $1.00 per square meter. It is reasonable to expect that by the time SPS is implemented, even better technological advances could be made.

3.2.1 Surface Accuracy

The reflector film must be supported by a structure that is capable of adequate surface accuracy. The sun subtends an angle of 1/2 degree of arc, so if the surface can be held to an accuracy better than this, say one or two milliradians, then the system performance would not be harmed by the errors. Current studies of radio frequency antenna structures indicate feasible accuracies of an order of magnitude better than this.

Indeed, the surface slope error of a large-area truss structure is approximately equal to the ratio of the cell size of the truss divided by the truss depth times the truss unit length. If the members of a truss can be established with a length error of one part in ten thousand, for example, the resultant error in the slope of a truss fabricated as deep as its local cell size would be about 0.1 milliradians. Thus, the objective of one milliradian slope accuracy without on-orbit adjustment is a reasonable one to propose. Particularly, the development of composite structures components of near zero thermal expansion coefficient area are very encouraging. In NASA Conference Publication 2058, p. 126, minor errors of 1-2 milliradians are shown to have only a minor effect on thermal performance of a collector and receiver, depending slightly on receiver temperature. This steering of individual facets does not seem necessary.

3.2.2 Structure Types

There is a variety of types of structures that are candidates for meeting the needs of SPS collectors. They include the aforementioned truss with flat facets, inflated paraboloidal membranes, geodesic-dome structures, pressure-erected self-stabilized shells, tension-stiffened surfaces, and pretensioned spoked wheels, as well as various combinations of these. The appropriate approaches are those that can meet the accuracy requirements against the environmental forces (characterized mainly by the solar pressure at 1×10^{-5} N/M^2) with a reasonable mass.

3.2.3 Structure Mass

To the structures engineer, a "reasonable" mass is usually less than the payload mass. If the payload were a photovoltaic blanket of 400 g/m^2, then a structure of 100 g/m^2 would be "reasonable", indeed attractive. For the present situation, the payload is the reflector film. A "reasonable" structural mass would thus be less than 5 g/m^2. Previous studies of SPS have yielded structural masses less than the structure's payload.

It is recommended that the following goals be established for the collector including structure:

Accuracy: 1 milliradian rms slope error

Mass: 10 g/m^2

Cost: \$ 1/M^2

These goals are considered to be realistic and feasible. They furthermore are advanced enough to provide a strong stimulation to the technologies pertinent to the collector subsystem, as well as to those pertinent to other related subsystems.

3.2.4 Recommendations

A program should be instituted that is aimed at the foregoing goals. The program should include: Development of films and structural materials with emphasis on long-term environmental stability, creation of an evaluation of various structural concepts for meeting the goals, examination of various means of erecting the collector in the final orbit, including deployment, assembly, space fabrication and a combination thereof, detailed design of attractive approaches, and construction of sub-scale models or full-size modules as appropriate and useful.

3.3 Advanced Thermal Power Cycles

Several approaches to solar thermal conversion are competitive at this time. Within our current abilities to quantify, the weights and costs of several concepts are competititve with each other as well as with the photovoltaic reference system. Two types are the Brayton and Rankine-cycle systems; many systems of both types are in extensive everyday use for generating power for electric utilities. Variations from the conventional systems include additions of Rankine bottoming cycles. In addition, various advanced concepts have been proposed that are less proven than the Brayton and Rankine cycles.

The discussion that follows is organized according to the principal thermodynamic cycle, that is the Brayton cycle, Rankine cycle and advanced concepts. In each case, the most fruitful areas for investigation of these concepts over the next five years or so are outlined. Considerable effort has already been invested by Boeing and Rockwell in analysis of these concepts. The discussion herein builds on these earlier studies and considers their outputs as a point of departure.

3.3.1 Improved Brayton Power Conversion Systems

Reasonable near-term improvements in closed Brayton cycle concepts and technologies have not been incorporated in the previous SPS systems analyses. Although further analysis and research and technology studies are needed it is already apparent that these improvements may have a very significant impact on the prospects for SPS and the choice of system concept and, in turn, on the prospects for SPS itself.

3.3.1.1 System Analysis

Intercooling during gas compression should be assessed in terms of its impact on performance of SPS. The power level of the power-generation modules influences ease of launching,

assembly in orbit, maintenance requirements and overall system reliability and should therefore be studied some more in combination with the overall system analysis.

Raising the pressure level within the system reduces the size of the various components but also requires thicker walls for the pipes and for the casings of the various components. The potential for reductions in weight and cost warrants further study.

Internally insulated ducts would permit separation of the functions of shaping the gas passage and containing higher-pressure gas. Within this concept, a refractory metal could form a thin and relatively cheap liner for a given duct, but that liner could be vented so that the pressure load is imposed on a cold pipe outside the insulation. Not only would the resulting low temperature for the strength member permit reduced weight but also the demand for scarce materials would be diminished. This principle, although used in design of HTGR for terrestrial application, has received no evaluation for use in space.

The usual working fluid for use in space-Brayton systems is a blend of helium and xenon which has a molecular weight selected for effective design of the turbomachinery. For a given molecular weight, this mixture has the best thermal conductivity among the suitable inert/gas mixtures, and therefore the heat exchangers can be made light and compact. Because of the high cost of xenon, other inert gas mixtures should be studied. A recent report (NASA TM 79322, Dec. 1979) found that the cycle efficiency of at least some Brayton systems can be raised through the use of a reacting gas as the working fluid; that concept should be evaluated for SPS.

In exploring Rankine cycles, Rockwell found significant reductions in weight and cost of SPS through the use of a steam bottoming cycle in combination with a cesium Rankine cycle. This gain was realized despite the fact that significant thermodynamic losses result from condensing cesium at constant temperature in order to heat, boil and superheat high-pressure water. A steam bottoming cycle could be even more effective in combination with the Brayton cycle, but this combination has not yet been explored for SPS in spite of the fact that the most efficient terrestrial power plants are now based on this combination. Radiation weight trade-offs tend to mitigate against low temperature bottoming cycles.

3.3.1.2 Materials

As cited earlier, existing technology on refractory materials should permit operation of Brayton systems at temperatures up to 1500°K (2250°F) through use of tantalum alloys. Niobium (or columbium) alloys lose strength at high temperature and are for this reason presently limited to about 1300°K) (1900°F); however, niobium has only half the density of tantulum and is less costly. Molybdenum alloys are about as strong at high temperature as tantalum, have density almost as low as niobium, but have not been much explored for use in fabricating pipes, turbines or heat exchangers. The very high thermal conductivity of molybdenum especially suits it for use in heat exchangers. In particular, molybdenum alloys warrant development and evaluation for use at temperatures of 1300°K and higher. The technology for fabricating heat exchangers from molybdenum should be evolved.

The ceramics, silicon carbide and silicon nitride, have inherent properties at 1650°K (2500°F) that suit them for use at that temperature, and the sialons have comparable properties. These comparatively new materials would be appropriate for use with inert gases, as planned for use with the Brayton cycle, and offer the potential for high performance using relatively cheap raw materials. The large program on ceramic gas turbines (over $100 million) sponsored by DOE should provide the basic enabling technology that would be the precursor of successful applicationk of these materials in SPS. The technology required for application of these promising materials in turbines for SPS should be evolved.

For electrical machinery in a Brayton system (in particular, for the generator and any motors or EM pumps required), the technology has already been demonstrated for 10000 hours with hot-spot temperatures of 980°K (1300°F); this technology would, in turn, permit cooling these components with a coolant supplied at 800-875°K (100-1100°F), a characteristic that relieves the problems of cooling these components.

3.3.1.3 Receiver

For the Brayton system, the solar-heat receiver requires significant improvement. In the existing studies of SPS, the Brayton receiver was heavier than that for the Rankine cycle, chiefly because the alkali-metal coolant of the Rankine cycle permits such high heat transfer rates. For the Brayton systems, use of such liquid alkali-metal coolants (whether pumped or circulated by the capillary forces in a heat pipe) should be explored as a means of reducing size, weight and cost of the receiver.

3.3.1.4 Heat Exchangers

In order to achieve its performance potential, the Brayton concept requires an effective recuperating heat exchanger. At the highest turbine inlet temperatures (1650°K or above), this recuperator should be made of a material such as molybdenum appropriate to temperatures of 1350°K (2000°F). The very high thermal conductivity of molybdenum also makes it a candidate for high-performance lightweight heat exchangers at lower temperatures. Evolution of technology on design and fabrication of such heat exchangers from molybdenum would therefore be very worthwhile.

If the solar-heat receiver is to be cooled by a liquid alkali metal, then some investigation of the high-temperature heat-source heat exchanger is also required. Effort is also needed on the design of waste heat exchangers that would transfer their heat to multiple radiator-coolant loops, thereby permitting design of radiators that would tolerate meteoroid penetration and still provide heat rejection with high reliability. Advanced heat pipe and liquid drop should also be considered.

3.3.1.5 Radiator

The waste-heat radiators for Brayton powerplants are relatively large, although less than one-tenth the size of photovoltaic arrays. On the other hand, the low temperatures of Brayton radiators compared with Rankine cycle system permit use of materials such as aluminum that have not only very low density but also very high thermal conductivity. Design studies and

technology development programs for Brayton radiators are required in order to evolve acceptable ways to fold and package the radiators for launching and to exploit heat pipes over the range of temperatures present in each Brayton radiator. The possibility of fabricating these radiators in space should also be explored.

3.3.2 Rankine Cycle Systems

Based on the Rankine-cycle point design evolved by Boeing for potassium and by Rockwell for cesium/water, the following analyses and tests are recommended:

(1) Evaluate rubidium as a working fluid in competition with potassium and cesium for turbine inlet temperature up to 1650°K (2500°F). Evaluate water and ammonia as working fluids in bottoming cycles. Quantify the demands for critical materials

(2) Evaluate vapor reheating during the vapor-expansion process. In particular, consider reheating by use of the sensible heat in the liquid from the liquid-vapor separator at the boiler exit

(3) Assess the optimum power from each power module, considering the masses and volumes desired for launching and considering as well the added reliability and increased maintenance resulting from the increasing number of modules

(4) In order to exploit the reduced density of molybdenum (10 g/cc) compared with tantalum (17 g/cc), evolve new molybdenum alloys. Investigate creep strength and weldability of these alloys for operating temperatures to 1600°K (2500°F). Investigate use of these alloys for fabrication of ducts, pump and turbine housings, and heat exchangers

(5) Test cesium condenser and water boiler for satisfactory performance under zero-g conditions. Evolve and demonstrate leak detection and automatic shutdown of the affected condenser and boiler

(6) Develop long-lived dynamic shaft seals (for example, a graphite face seal) for sealing between an alkali-metal vapor and space

(7) Analyze and thereby quantify the benefits from use of existing technology for hermetically sealing the alkali-metal turbogenerator within the present limitation of $975^{o}K$ ($1300^{o}F$) hot-spot

(8) Consider use of a superconducting generator cooled with liquid helium if this action appears justified by current programs for electric-utility applications

3.3.3 Advanced Concepts

The potential exists for markedly improving performance of solar-thermal systems by increasing overall efficiency of the thermal powerplant by 30-50%. Accordingly, the required energy collection might be diminished by 23-33% and the heat rejected decreased by 45-55%. These changes would have a significant impact on the weight and cost of both the solar collector and the radiator.

Concepts for achieving these improvements are now either incompletely evaluated for application in SPS or insufficiently mature in their development to warrant substitution at present for the reference photovoltaic concept. But the magnitudes of the potential gains are great enough that their exploratory investigation should not be neglected.

Investigation of these concepts should have two initial phases:

(1) System studies should define the most advantageous way to apply a given concept to SPS, should quantify the potential benefits from use of the concept, and should delineate the principal technical issues that impede the concept's application to SPS

(2) If the benefits quantified in the studies justify further investigation, then a follow-on technology program should address the principal technical issues delineated by the study

Inasmuch as the investigation of each advanced concept would have these two phases, the two phases are not further discussed herein, it being understood that for each concept the two phases are to be conducted sequentially. A continuing research program should be directed toward generating the necessary data, such as high temperature materials properties and interactions needed for Plan 1.

3.3.3.1 Thermionic Conversion

For over 20 years thermionic conversion has been under continuous investigation for generation of space power. At present, the investigation is centered at JPL and is focused on use of heat from advanced high-temperature nuclear reactors. Earlier studies of thermionics at JPL also considered the possible use of solar energy.

For perhaps the first 15 years, thermionic converters were investigated for operation at 2000-2100^{o}K. Under a Lewis-sponsored program, one converter operated stably for over 40,000 hours at 2000^{o}K. Although the recent program has centered on achieving satisfactory power and efficiency at lower operating temperatures of 1600-1700^{o}K, the early results show the potential for operation at high temperature.

Because each thermionic converter produces about a kilowatt of power, the concept has the potential for insensitivity to failure of single converters. The ability to operate at high temperatures also suits the thermionic converters for production of power either by themselves or as a topping system for a lower-temperature cycle.

Thermionics were briefly studied already as one concept for SPS. We recommend that this study be reviewed in light of the current state of the art and that, if warranted, the study be extended. In addition, the thermionic concept should be evaluated as a topping system for a Rankine cycle.

3.3.3.2 Concepts for Very High Temperature

The usual concepts for solar-thermal power use focused solar energy to heat a metal wall to a high temperature and then transfer this heat to the thermo-dynamic cycle's working fluid. In that event, the metal wall must be somewhat hotter than the working fluid, and the temperature limitations on this metal wall impose a limit on the efficiency that can be achieved by the thermodynamic cycle.

Concepts that heat the working fluid above the wall temperature have the potential to raise cycle efficiency. One concept would pass focussed sunlight through a window and heat potassium vapor by absorption of the solar energy in the volume of opaque potassium vapor, that is, by volume absorption. In concept, the potassium vapor might be heated to 3000-3500°K, which is 1500-2000°K above values practical in the usual potassium-Rankine cycle.

Such hot potassium vapor could not flow at high speed past turbine blades in the conventional manner without heating them beyond the limitations of turbine materials. The "wave-energy exchanger" provides a concept for potentially transferring useful energy from the hot potassium vapor to a lower-temperature working fluid such as helium. By that device, the potassium would be expanded, cooled and relieved of some of its energy, this energy being used to compress the cool helium. The helium would give up this energy by passing through a conventional turbine.

In combination, the "volume absorber" for heating the potassium vapor and the "wave-energy exchanger" for extracting its useful energy provide the basis for a power-conversion-system concept relieved from the usual temperature limitations imposed by wall materials. The waste heat in the still-hot potassium vapor can, of course, be transferred to a lower-temperature cycle, which would operate with its usual efficiency and performance. In this way, the power output of the very-high-temperature potassium cycle is a direct addition to the output of the lower-temperature cycle, reducing the heat energy required and the thermal energy rejected for a given electric power output.

Although this approach to design of the power conversion system is very valuable in principle, its technology is not yet advanced to the state at which one could exploit the concept with confidence. However, experimental high temperature compressors have been built and shown to operate at temperatures to $2500^{O}K$. At the present time further experiments are in progress involving test machines to determine the efficiency of wave energy exchange. The future benefits of concepts such as this are so great that the overall SPS program should explore them prior to embarking on the construction of the first SPS.

3.4 Life Expectancy, Failure Rates, and Long-Life Capability of Rotating Machinery for SPS Application

One of the more obvious concerns regarding feasibility of a solar thermal SPS is the reliability, maintenance and life expectancy of rotating machinery such as turbines, electric generators and pumps. Large ground-based utility turbines and generators are routinely designed and operated for 30 year life, with scheduled shutdown inspection and maintenance once every few years. A capacity utilization factor (on-line service) of 75% is typical for an entire fossil-fueled steam power plant but only a small part of the total down-time is attributable to rotating components. Most failures are related to corrosion in the plumbing, boilers, exhaust stacks, condenser fouling, electrical control failures, etc. These problems can be largely avoided in a space environment due to the absence of air leaking into the steam loop, and the absence of moisture, dust, corrosive exhaust gases, and bio-fouling. Also, with a very low turbine specific mass, it is economical to use high-alloy stainless steels throughout the design which are corrosion resistant if trace amounts of oxygen are introduced to form a protective oxide film on the surfaces. The high purity metals used will have little tendency to exude contaminants such as silicon which can cause scaling problems. It is not anticipated that water maintenance or in-service water treatment will be required, if initial descaling runs are made in the steam loop with a high pH fluid during production testing of the power module.

3.4.1 Reliability and Maintenance

The basic reliability goal for an SPS is uninterrupted production of rated power (excepting eclipse periods), in the most cost-effective manner. This requires determination of the optimum levels of reliability development and operational maintenance. For the cesium/steam point design, a rather high power availability of 90% of total capacity was chosen as a working target. Consequently, each of the 318 power modules was oversized 10%. Achievement of the above target requires the following:

(1) Standby repair crews capable of servicing any satellite on 24 hours notice

(2) High inherent component reliability achieved through extensive stress-to-failure testing in development and production samples

(3) Redundant fail-safe system design

(4) Extensive monitoring instrumentation and automated diagnostic/self-shutdown circuitry at the power module level. Typical measurements are system pressures, temperatures, flows, voltages, actuator positions, and vibration signatures of critical rotating units. Summary data from each module is transmitted to the on-orbit and ground control centers

(5) Modularized replacement units at each component level to facilitate rapid maintenance. A boiler feed pump, for instance, could be changed out in 10 minutes if quick-disconnects are provided for all fluid, electrical and structural connections

As discussed in later sections, the bulk of failures are expected to involve small components (sensors, controls, pumps, etc.) which can be readily replaced. It is estimated that major failures which are not practical to repair in service (turbine bearings, generator windings, etc.) would result in less than 10% loss of generating capacity in 30 years. The power modules are 10% oversized to absorb this loss and still meet rated capacity, with some replacement of turbines and generators in later years.

Achievement of a 90% availability (vs. 75% for ground utility power/stations) is also based on the following SPS advantages:

(1) No problems of atmospheric air leakage into a sub-atmospheric fluid loop to cause corrosion or degrade condenser performance

(2) Materials in the SPS fluid loop will be highly corrosion resistant. Ground utility boiler tubes and turbine blades are typically of low alloy steel. The presence of silica and other metal impurities which cause scaling will be greatly reduced in the SPS

(3) Absence of gravity forces virtually eliminates radial loads on turbine and generator bearings

(4) Shutdown for routine inspection or maintenance will not be used, and will be designed out of the system by fail-safe features, rigorous development and quality control, production burn-in testing, and automated monitoring of turbine/generator vibration signatures

3.4.1.1 Failure Rates

The large number of power modules (318) increases the total satellite parts count, but not the failure rate per module. The latter should actually be less in smaller power sizes, since more intensive development can be afforded and the auxiliary systems are usually simpler. Also, the proportion of total satellite capacity unavailable at any one time is reduced, due to higher redundancy.

Although rotating machinery is traditionally expected to have a higher failure rate than solid state equipment, the SPS turbogenerators are expected to require much less replacement than solid state antenna components or specialized components, such as the klystron tubes.

The chief drawback of a small power module size is an increase in the total number of maintenance and repair tasks. Seventy-five percent of the 318 power modules are expected to have at least one failure within their 30 year life. Most of these will be of a minor nature (sensors, wiring, controls, seals, pumps, etc.) that can be quickly repaired or replaced. Major

failures of the rotating units such as cracked turbine blades and failed bearings would be much less frequent and would normally be handled by simply shutting down and abandoning (and possibly replacing) the failed unit. Interconnections between power modules permit sharing of cesium flow in such cases. To maintain rated capacity, it may be necessary in the later stages of satellite life to replace entire turbines, generators, and even power modules. These would be refurbished in the orbiting maintenance shop or returned to earth for rebuilding. It is possible that a power module could be changed out during a 72 minute eclipse period. The connectors involved are 2 cesium, 2 steam, 2 electrical power, 1 electrical control (multi-pin), and 4 structural. In the zero-g environment, a power module is easily removed through the bottom of the aborber disc, away from interference by adjacent plumbing, wiring, etc. Extending the module "down-time" several hours, if required, would not be serious since eclipses occur at ground-station midnight when power demand is minimum.

3.4.1.2 Cesium/Steam Interleaks

The possibility of steam leakage into the cesium loop can be reduced to a small probability, and standard means are available for preventing subsequent over-pressure conditions and cesium contamination in adjacent power modules. This is considered less of a problem than that from the accepted failure rates for turbine blades, generators, etc.

High pressure steam leaking into the cesium system would cause a spontaneous exothermic reaction (but not a detonation). It could also cause an overpressure condition and extensive corrosion of the refractory metals in the cesium turbine, boiler, and flow loop. An intermediate heat transfer fluid could be used to prevent direct contact of cesium and steam in the event of a leak, but a weight penalty would be involved. Double-walled boiler tubing would impose less of a penalty in these areas. The recommended solution is to use single-walled tubing which has been proof tested and leak tested to stringent requirements, with all joints of a brazed-sleeve design to avoid the potential cracking problems associated with welded connections in a thermal cycling and vibrational environment. The tubing coils would be supported by streamlined radial struts at

appropriate intervals to separate the natural vibration frequencies of the tubing spans from exciting frequencies. In the event of a failure, failed units would be shutdown, drained, and either repaired, replaced or abandoned. Overpressure conditions in the condenser shroud would be prevented by a burst-diaphragm with a double-ported vent duct on top of the condenser shroud to achieve thrust-balanced venting of the reaction products (H_2, CeOH, H_2O or Ce) away from adjacent turbo/generator sets.

3.4.2 Technology Advancement and Verification

The chief areas requiring technology advancement are:

1. Material properties data, especially long-term creep
2. Welding of refractory metals (electron beam and laser techniques)
3. High temperature liquid metal pumps
4. Turbomachinery
5. Zero-g condensing
6. Reliable, long life electric generators
7. Refractory metal properties, especially long-term creep
8. Cesium erosion and corrosion data
9. Hydrodynamic bearings
10. Shaft seals

Technology verification can be accomplished by subscale and full scale testing of complete modules, both on ground and in orbit. Potential fire hazards from cesium and air leaks will require elaborate precautions during ground development tests. Ground vacuum chambers or helium purge systems will be required.

Development and verification of the integrated condenser concept will require subscale and full-scale demonstrations on the ground and in orbit. Ground testing would involve placing the axis of the annular coil bank in a vertical direction, to observe the centrifuging action of the

rotating vapor mass on the cesium condensate without a radial gravitational force component. Development risk is not considered great since additional whirl velocity can be easily provided if needed to obtain required condensing performance. Stress-to-failure testing with over-design pressure, temperature, vibration and corrosion environments would be mandatory.

With a double-flow cesium turbine, the shaft seals can both be located at the coolest end. However, it will be necessary to find face-seal materials which are compatible with each other and also compatible with cesium.

3.4.2.1 Development Risk

Given the fair state of refractory metal technology, cesium corrosion data and hydrodynamic bearing development, the risk in developing a satisfactory cesium turbine is considered moderate. Even if SU-31 alloy should prove unfeasible, TZM and molybdenum would provide a reliable fall-back position although turbine weight would increase somewhat due to the thicker disc and casing sections required.

3.4.2.2 Conclusions

Achievement of a 90% capacity utilization factor for the SPS is considered feasible, although detailed studies may show, that a factor of 85% is more cost-effective. Due to the presence of repair crews, the requirements for component reliability may be less stringent than those now used for unmanned satellites.

3.5 Space Radiators

Among the most important factors influencing the feasibility of Satellite Power Systems is the necessity of rejecting the waste heat by radiation. High cycle efficiency generally implies a low heat rejection temperature and consequently a large radiator area and mass. This tends to conflict with the basic requirement that any space-based power plant have minimal mass. The

balance between cycle efficiency and radiator mass thus forms a central design problem for SPS systems.

In most designs the radiator is composed of a vast array of heat pipes and radiator tubes through which flows the working fluid. The tubes must be sufficiently massive to minimize micro-meteoroid penetration; in addition, transport of the fluid over large distances is required. Radiator mass and the thermal management system in such designs comprise a large fraction of the total SPS mass.

The development of heat pipe technology has continued to advance since the thermal cycles were deemphasized several years ago. Also new data has shown that the model used to evaluate meteoroid penetration is probably too severe; therefore, the header tube and heat pipe model should be reevaluated.

Despite the crucial impacts that the radiator has on both weight and reliability of large thermal power systems, the technology for such radiators has received very little attention. In the discussion that follows, radiators will be considered in terms of near-term technology and advanced concepts.

3.5.1 Near-Term Technology

Conventional radiators use a circulating fluid (whether liquid or vapor and whether circulated by pumps or by capillary forces) to transport heat throughout the radiator. Such coolant passages are armored so as to protect against meteoroid penetration and segmented into multiple channels so as to tolerate meteoroid penetration whenever it does occur.

Primary and secondary coolant streams are also considered occasionally. The primary streams would be heavily armored and would do the principal job of distributing heat throughout the radiator's area. The waste heat from each primary stream would be transferred to multiple secondary streams, and from those secondary streams, the heat would be conducted along solid fins that would then radiate the heat to space. The segmenting of the primary stream into

multiple streams and thence to fins are all intended to decrease vulnerability to meteoroid penetration, to reduce radiator weight and to increase reliability. The design of radiators for SPS will depend not on just the techniques for design but also on the constituent technologies on which the design techniques are based.

3.5.2 Constituent Technologies

Meteoroid-penetration criteria are crucial to design of lightweight, reliable radiators. The validity of the data from Pegasus has been questioned because the actual experience in space differs from what the Pegasus data would predict. The topic of meteoroid penetration should be reassessed with the view that past efforts might require extension. Such a program would help not only the thermal power systems but also heat rejection from the power processors for photovoltaics as well as the photovoltaic arrays themselves.

The nature and scale of SPS are sufficiently different from those of other space power systems that technology specific to SPS is required. Detailed studies of radiator design are required in order to define both "optimum" radiator designs and crucial problems limiting those concepts. The selection of materials and the known properties of these materials should be appraised. Techniques should be evolved for compacting the radiators for launch and for erecting them in space. Concepts for foldable pipes (such as in NASA TM X-1187) should be evaluated in competition with rotating seals and weldable joints for use in erecting the radiators. Concepts for fabricating radiators in space should also be studied as ways to provide great compactness of radiators during launch; as an extension of this, leak detection and repair should also be studied as means of providing highly reliable but lightweight radiators.

Heat pipes have for a long time been considered as the principal mechanism for distributing waste heat throughout the radiator's radiating surface. The weight reduction that accompanies segmentation of the radiator is the crucial reason (English and Guentert, "Segmenting of Radiators for Meteoroid Protection," ARS Journal 31, 1162-4 (1961)). In such a radiator, the

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heat-pipe circuits range from very long runs, in order to transport heat to the farthest reaches of the radiator, to very short runs that simply convey the already-distributed heat to the radiating surface itself and are occasionally called "vapor-chamber fins." Over this range of application, the requirements imposed on the heat pipes differ considerably. The long runs require the ability to transfer large amounts of heat in the vapor phase through a duct of a given cross-sectional area. The vapor-chamber fins require low vapor pressure and low liquid density in order that the vapor chamber might be as light as possible per unit of surface area. The wide range of operating temperatures also affects selection of working fluid and containing material. The Brayton cycle presents a special problem in radiator design for use of heat pipes inasmuch as the waste heat is to be rejected over such a wide temperature range even within a single power system; on the other hand, this wide temperature range produces for the Brayton system the lowest fluid flow and inventory for those concepts using pumped liquid circuits for heat rejection. Further investigation of heat pipes for radiators over this range of conditions is required.

3.5.3 Radiator Design

A given radiator design is based on an actual or assumed state of constituent technologies and on a given set of constraints, such as volume available in the launch vehicle. It's time to reconsider radiator design for the thermal power systems with the view of improving their weight, reliability and packaging for launch. Methods to cope with the wide range of heat-rejection temperatures from the Brayton cycle should receive special attention. The possibility of radiator fabrication in space should also be studied.

As the constituent technologies advance, the radiator-design studies should be reviewed and reassessed every two or three years.

3.5.4 Advanced Concepts (Dust and Liquid Drop Radiators)

3.5.4.1 Dust Radiators

An entirely different approach to the radiator problem may yield significantly improved designs. This particular approach is based on the fact that small particles can have almost unlimited ratios of area to mass since the ratio is inversely proportional to the size of the particle. Such "dust" particles could then be very efficient radiators. The particles are heated in a container and projected in a stream to be caught by another container and reheated, thrown again, etc. While the particles are traveling from one container to the next, they cool, losing their heat by radiation.

A highly simplified analysis of this concept has recently been developed. In this analysis it is assumed that the mass/unit exit area of the chamber is a given number, that the kinetic energy of each particle is 0.5 percent of the amount of heat lost by the particle in its flight, that the amount of particles inside the chamber are about 20% of the particles in the stream, and that the number density of the particles in the stream is such that only about one-half of the solid angle seen by the particles in the flow of the stream is blocked by other particles.

3.5.4.2 Liquid Drop Radiators

It is proposed in addition that a stream of liquid metal droplets about .1 mm in diameter be used as a radiator. This concept retains the low-mass advantages of a dust radiator, and has the additional advantages of allowing heat transfer by conduction in the heat exchanger and ease of manipulation.

In particular, the generation of a uniform, collimated stream of liquid drops is a well-developed technology, and collection and transport of the cooled drops (after radiating) appears to be a solvable problem. One rudimentary collection scheme is presented below and more efficient designs are doubtless possible.

A governing factor in design of a liquid droplet radiator is mass loss via evaporation. The mass required to replenish the evaporation must of course be included in the overall radiator mass for comparison with other radiator schemes. It has been found, however, that for a given radiator temperature range, liquid metals exist for which evaporation loss for a 30 year SPS lifetime is sufficiently small that the liquid droplet radiator is still considerably lighter than a tube radiator.

Fig. 3.5.1 shows a possible configuration for implementation of the liquid droplet radiator. The use of paired modules eliminates the need for a long return loop for the radiator liquid. The liquid absorbs the heat rejected by the working fluid in one module and is projected in a thin converging sheet toward the second module which collects the radiatively cooled liquid in a rotating drum. The collected liquid absorbs heat from the thermal engine of this second module and is projected back to the first module to complete the loop. A sheet rather than conical configuration for the drop stream minimizes the solar radiation absorbed by the stream.

Fig. 3.5.2 shows the principles of drop generation and collection. The generator is an array of holes or nozzles with provision for rapidly varying the pressure of the fluid (vibrator) to achieve a uniform drop size. This technique is well established in the operation of ink-jet printers. The collector is a rotating drum so as to form the drop stream into a continuous liquid by centrifugal acceleration. Only modest rotation speeds are required to develop a sufficient head for the pump.

The principal requirements for the radiating medium are a low melting temperature and low vapor pressure. Current SPS designs incorporate engines with rejection temperatures of 700-1000°K (peak temperature for the liquid drop radiator) so a melting point in this range and below is desired to avoid the complications of manipulating solid particles. Of course, a lighter radiator may enable even lower rejection temperatures to increase thermal engine efficiency so that ideally the radiator medium should have as low a melting point as possible. Also the vapor pressure at the radiator temperature should be low enough to avoid excessive mass loss due to evaporation.

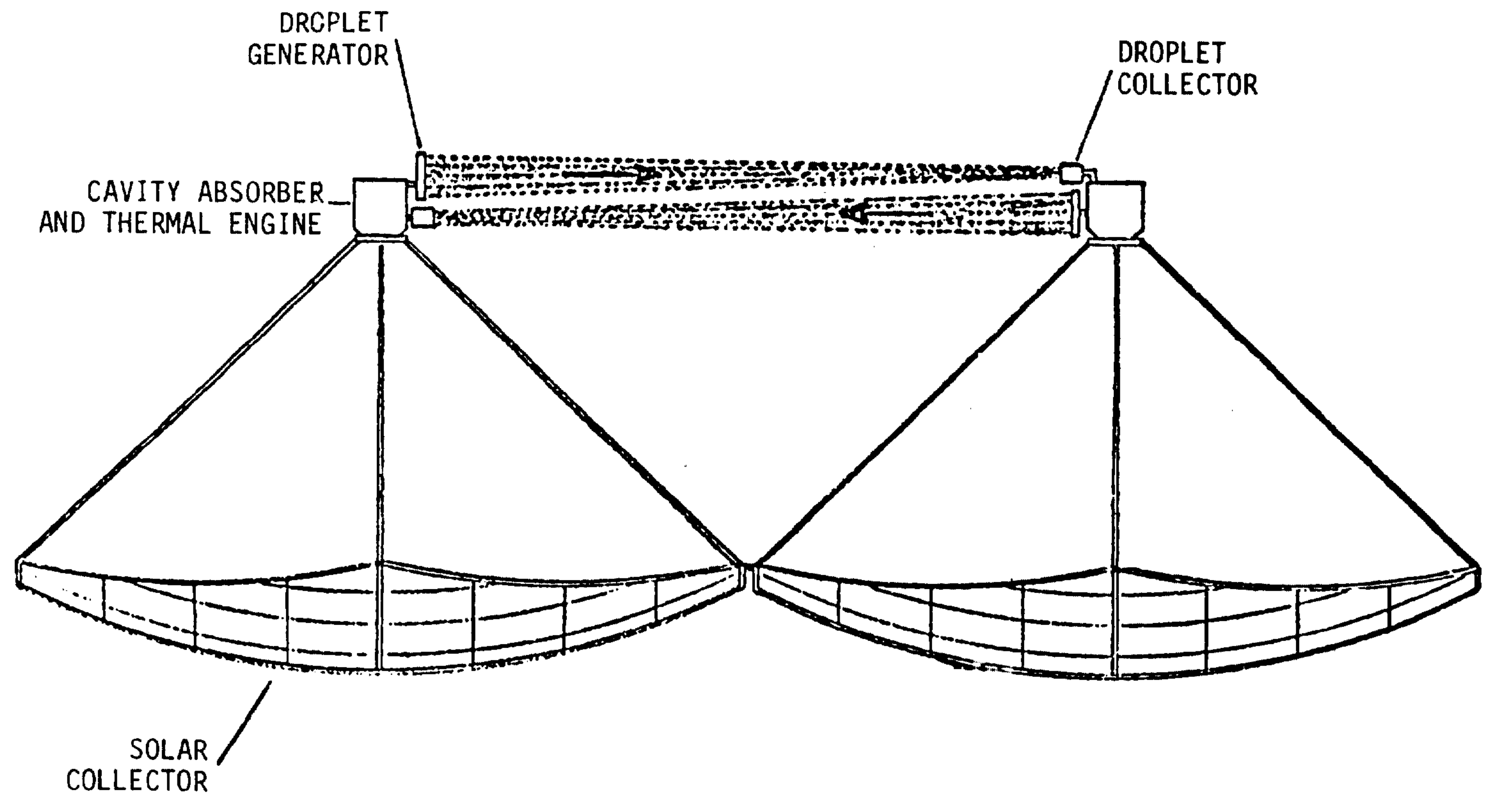

Figure 3.5.1 Liquid Droplet Radiator Configuration

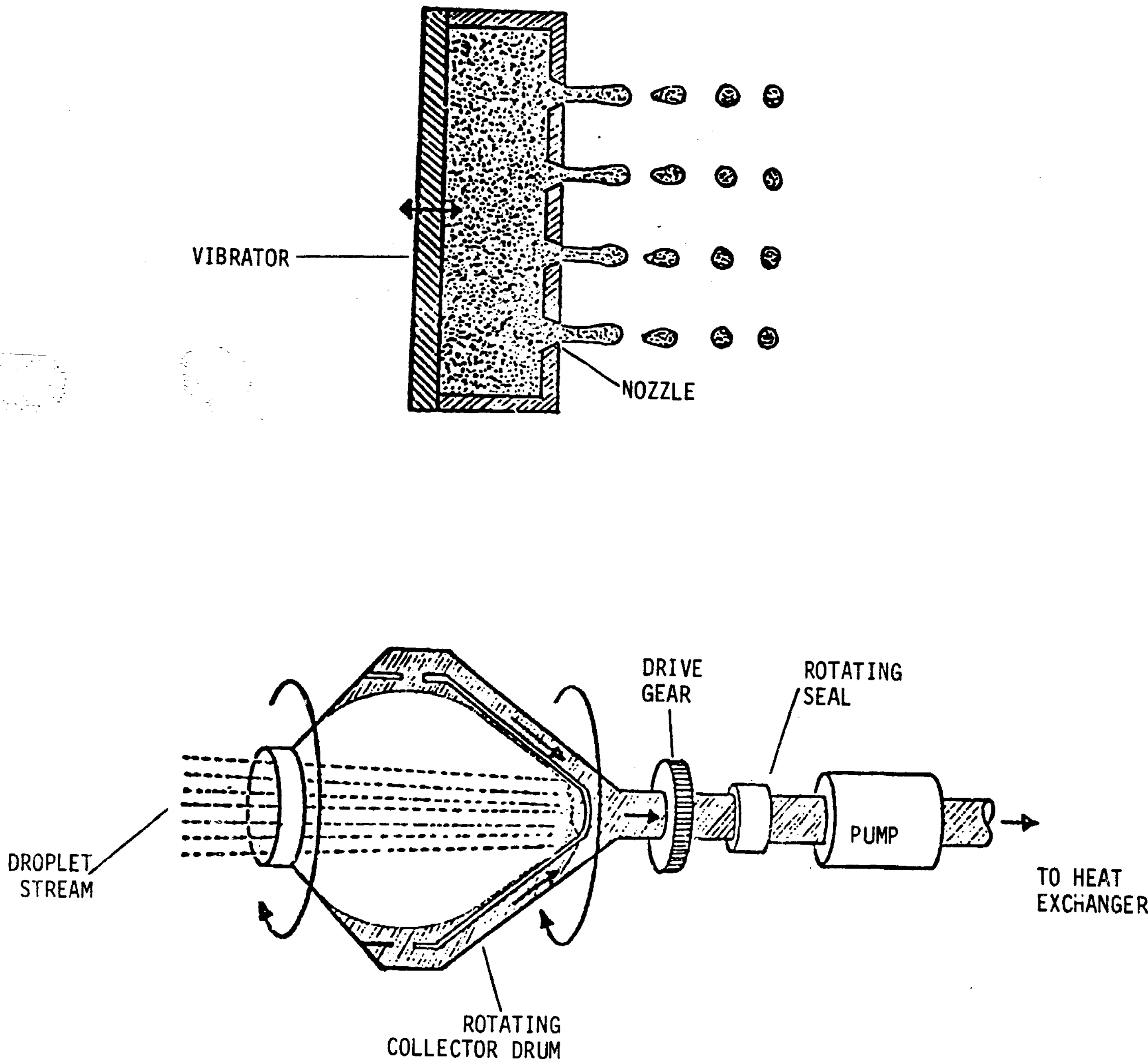

Figure 3.5.2 Drop Generation and Collection System

Initially, silicone fluids were investigated for this application due to their low vapor pressure. However, the stability of these fluids under repeated temperature cycling is questionable and liquid metals appear to be more attractive radiator media.

Table 3.5.1 shows the relevant properties of some elemental liquid metals and Figure 3.5.3 shows the vapor pressures of these metals. Among these, gallium and indium have the lowest melting points and also exhibit low vapor pressures. For large scale installations, these metals may be too rare, however, to be practical. Lithium may prove useful, due to its light weight and large heat capacity. Above 500^{O}K, however, its vapor pressure is excessive. Tin appears to be the most practical radiator medium, as it has a small enough vapor pressure to be usable at 1000^{O}K and thus affords quite a wide operating temperature range from 505^{O} to 1000^{O}K. Aluminum's high melting point (933^{O}K) restricts its use to a narrow range of high temperatures, while lead may be alloyed with tin to produce a low melting point eutectic (melting temperature 460^{O}K for a 60% tin mixture). A wide range of binary eutectics was investigated but the lead-tin mixture was the only one among those having low vapor pressure components with a melting temperature appreciably below that of tin.

The mass loss for these materials prove to be surprisingly low; this mass loss is plotted versus temperature in Figure 3.5.4. Also shown are the corresponding values for Lithium (with T_1=453^{O}K). The mass loss for tin is less than the mass of the liquid in the radiating slab for temperatures of 1000^{O}K, for a thirty year life, while for lithium one is restricted to temperatures below 550^{O}K. A rule of thumb is that the vapor pressure should be less than 10^{-7} mm at the peak droplet temperature.

Metal	Melting Point	Boiling Point	Heat of Fusion	Sp. Heat (liquid)	Th. Cond. (liquid)	Density (liquid)	Surface Tension
Ga	303°K	2523°K	$80.1 \frac{J}{g}$	$0.41 \frac{J}{g - °K}$	$0.33 \frac{W}{cm - °K}$	$6 \frac{g}{cm^3}$	$740 \frac{d}{cm^2}$
In	429	2348	28.4	0.27	0.42	7	600
Li	453	1600	410	4.22	0.42	0.5	--
Sn	5C	3000	59.4	0.26	0.33	6.8	550
Pb	600	2013	23.8	0.15	0.15	10.5	420
Al	933	2483	389	1.08	0.84	2.3	900

Table 3.5.1 Properties of Liquid Metals

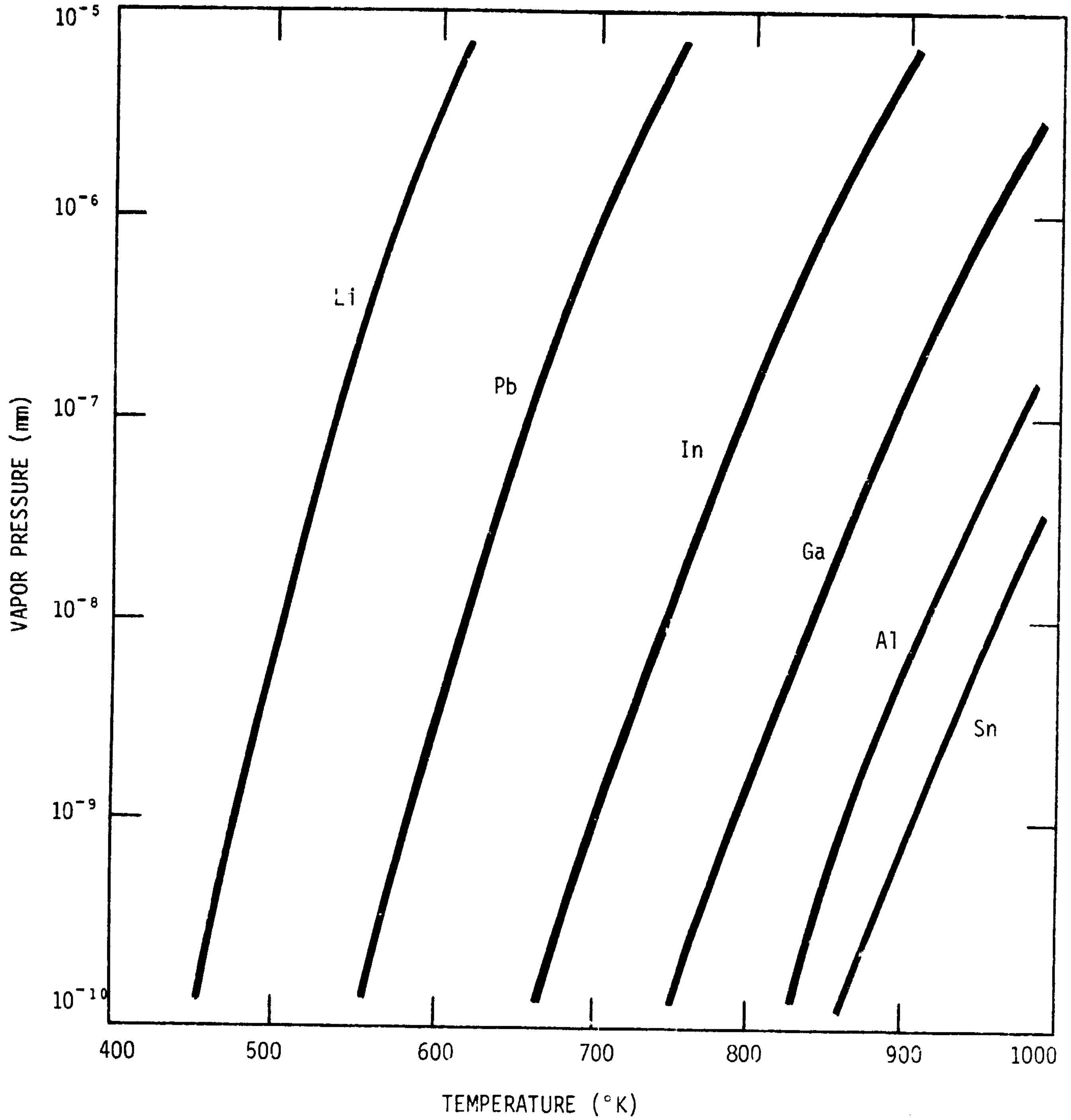

Figure 3.5.3 Vapor Pressure of Liquid Metals

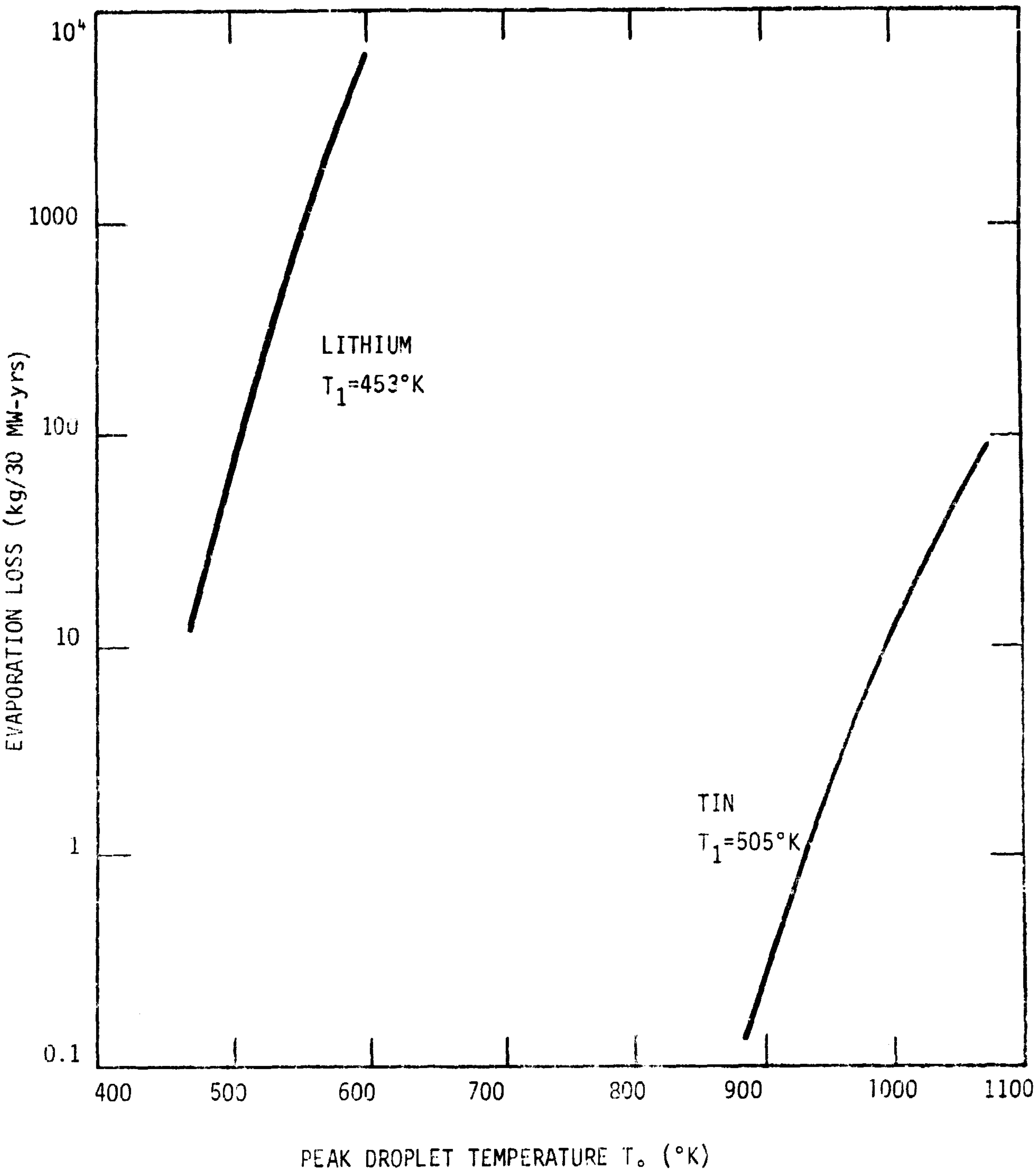

Figure 3.5.4 Mass Loss vs. Temperature

While conventional tube type radiators for space power systems typically weight 500-2000 kG per MW of radiated power, a liquid drop radiator is 10 times less massive. Since radiators comprise a large fraction (up to 40%) of the total SPS mass in conventional designs, liquid drop or dust radiators offer a enhancement of the feasibility of SPS thermal systems. Because of the low mass, significantly lower rejection temperatures are feasible with droplet radiators and thus the efficiency of SPS thermal engines may be markedly improved. It may even be possible, using, say, low melting point eutectics, to use steam Rankine cycles in space, heretofore impractical due to the low rejection temperatures.

The technology for production of droplets is well established and the simple radiator configuration illustrated here offers at least a starting point for droplet collector designs. Also, fortunately, there exist liquid metals with low enough vapor pressures to be practical over 30 year SPS lifetimes. While the elementary analysis of the operation of a droplet or dust radiator presented here shows the great promise of this concept, optimization and more detailed design is necessary to fully assess the potential of the droplet radiator.

3.6 Conclusions

All the concepts (photovoltaic as well as solar thermal) require substantial advances in technology in order that the goals set for SPS might be achieved. Because of this, none of the concepts has such low risk that it can be relied upon to the exclusion of others. Therefore, all the concepts competitive at this time should be supported until sufficient information is available to permit narrowing the choice. If arbitrary narrowing of the program is required by budgetary pressures, then prudence would require that the competitive concepts to be supported should not have a common question of feasibility such as radiation damage.

3.6.1 System Reliability

Some mission planners incorrectly consider the solar-thermal power systems to have inherently a lower reliability than photovoltaic systems. This view stems from two basic viewpoints, viz., (a) the lower multiplicity of elements in solar-thermal systems compared with photovoltaic and (b) what is considered to be an inherently limited life for rotating machinery. In fact, the number of power-generation modules for a solar-thermal version of SPS could readily be of the order of 100, a value high enough to give the spacecraft very high reliability; an analysis of this reliability issue is highly desirable in order to provide specific, definite information on this subject as background for the mission planners.

Consider, for example, that the reliability of each power-generating module is 0.95. Although there would then be only one chance in 170 that all 100 power modules would operate without failure, there is also only one chance in 35 that more than 9 would fail. Even in the complete absence of maintenance or repair, such a low failure rate is readily compensated for by initially installing 10% excess capacity. And with that 10% allowance, there is only 1 chance in 2000 that power output would fall below 95% of the selected end-of-life power.

Even higher reliability numbers could be realized, if that were ever necessary, simply by using a larger number of power modules, say, 1000 modules of 5-10 MW each. For a unit reliability of 0.95 as before, provision of only 8% excess capacity at mission start would yield 0.999 reliability of producing rated power at the end-of-life and only one chance in a million that end-of-life power would fall below 98.7% of the desired value. (Power fluctuations exceeding these variations will result for every concept, including photovoltaic, because of varying atmospheric attenuation of the microwave beam.) If maintenance of SPS in geostationary orbit is practical, then even higher reliabilities can be achieved. The age-old criticism of the reliability of dynamic power systems because they have low mutiplicity of elements is overcome by the sheer scale of SPS.

3.6.2 Design and Fabrication of Components

The solar-thermal power systems raised issues in mission execution that remain largely unresolved, problems concerning the packing density of the components during launch and concerning construction and maintenance in space. Inasmuch as these problems were defined in the SPS mission studies, now is the time for the component-design specialists to study how the components might be designed and built so as to overcome these problems. The approach should be iterative with first the component-design specialists attempting to relieve the foreseen problems, and then the mission analysts should evaluate the impact of the proposed solution on the overall performance of the resulting SPS. Several such iterations should produce design concepts for SPS significantly superior to those now in hand.

3.6.3 Solar Concentrators and Receivers

Lightweight high-performance focussing solar collectors are common to all the solar-thermal systems as are the solar heat receivers that absorb this heat and transfer it to the working fluid. For the receivers, the state of the art is still rather primitive and considerable effort on design and experimental evaluation of concepts is required. Such an effort would focus on achieving low weight, high cycle temperature, good thermal efficiency and resistance to thermal shock on entering and leaving the Earth's shadow.

Low weight was achieved in the receiver concept for the alkali-metal Rankine systems by exploiting the high-flux capabilities of the alkali metals. The receiver for the Brayton systems was considerably heavier because of the lower heat fluxes achievable by gas-cooling the receiver. Some investigation of Brayton receivers is required to explore the feasibility of reducing receiver weight through use of flowing alkali metal as the heat-transfer medium for cooling the receiver and heating the Brayton's gaseous working fluid.

3.6.4 High Temperature Materials

Existing technology of refractory metals (chiefly tantalum alloys) is such that either Brayton or alkali-Rankine systems could be developed for peak cycle temperatures of 1500^{o}K (2250^{o}F). A limited amount of data on refractory metals shows that higher temperatures up to perhaps 1600^{o}K (2400^{o}F) may also be practical. Molybdenum alloys appear to be competitive in strength with and to have only 60% of the density of tantalum, but not many molybdenum alloys have been developed, nor have techniques been evolved for fabricating receivers, heat exchangers, or turbines of this metal. On the other hand, the molybdenum alloy TZM has been creep tested for periods exceeding 5 years at 1350^{o}K (2000^{o}F) and 1400 MPa (20000 psi), and moly-alloy turbine blades have been tested in turbines operating on potassium vapor for a total of 10000 hours without encountering basic problems.

On the basis of existing data on materials, ceramics might permit even higher temperatures for Brayton systems, but no effort has gone into their investigation for SPS. ARPA invested over $30 million in ceramic materials for gas turbines, and very substantial advances in material properties and in knowledge of how to use these materials were evolved. On the basis of material properties alone, ceramics are suitable for use at temperatures of at least 1650^{o}K (2500^{o}F). Because of the success of this materials program, the Department of Energy has begun a program for use of these ceramics in automotive gas-turbine (Brayton-cycle) engines; the projected value of the current program is about $150 million. Some effort in the SPS program should focus on adaptation of this rapidly-moving technology to SPS.

Because radiators for both Brayton and Rankine systems are a substantial portion of total system mass and because the potential for meteoroid penetration of their fluid passages tends to degrade system performance with operating time, substantial effort is required on the design of this critical component in order that we might achieve low mass and high reliability. Advanced, novel concepts in radiator design are considered in this report as well as the technology for more conventional radiators that can be folded and packaged for launching and then erected or deployed

in space. Exploitation of man in space for radiator assembly, erection and maintenance has received only cursory attention.

A seldom recognized advantage of the dynamic power systems (whether Rankine or Brayton) is that they produce power in a highly usable form that greatly simplifies the problems of power processing. Their output power will be AC with a frequency of a kilohertz or two and a potential of a few kilovolts. This power would also be regulated as to frequency and voltage. The energy losses in and the heat rejection from the power processor are thereby much reduced. The generators or motors can also handle significant amounts of reactive power, if that is desired.

Table 3.5.5 is a proposed GBED for solar thermal SPS system.

4. ELECTRIC POWER DISTRIBUTION PROCESSING AND POWER MANAGEMENT

The economic practicality of the SPS is greatly affected by the tens of thousands of kilovolt operation that is necessary to operate the power transmitters directly from the solar array or via power processors, and which is also required to minimize the weight of the power conductors and ultimately the transportation cost.

The technical feasibility of the SPS will depend on the technology readiness of techniques, components and equipment to reliably distribute, process and interrupt hundreds of megawatts of power at tens of thousands of kilovolts. The combined requirements of dissipating concentrated heat and preventing breakdowns due to corona in the insulating materials or arc overs due to plasma discharges are much more severe in space, that is, in the absence of the insulating and thermal transfer properties of air, than in similar high power and high voltage ground applications.

The technical feasibility of the proposed SPS power distribution and processing concepts hinges on the successful realization of high power kilovolt ultrafast protection switches (one circuit breaker for each high voltage; 600,000 per SPS for the klystron concept) required to protect the transmitter tubes for the normally occurring tube arcs.

4.1 Power Distribution System Configuration

The approach suggested by the study contractors is to combine the output of solar array sections and then redistribute it to load centers that individually account for between 0.5 and 3% of the total transmitter load power.

Consideration shall be given, through SPS system studies updating, to enhance system reliability and to limit the rating of the power distribution and processing equipment that need to be developed by having each of the load centers powered from separate solar arrays and power distribution channels.

Separate solar array sections should also be considered for recharging of the energy storage elements and to power the other spacecraft subsystems. AC distribution shall be carried on as an option until the economic practicality of the high power tens of kilovolts, fast response, DC transmitter tube protection switches has been established.

4.2 Power Processing Equipment

Requirements definition studies should be expanded to ascertain that the weight and efficiency estimates of the proposed power processing and protection equipment are based on requirements that are sufficiently complete so as to preclude gross errors in the predicted SPS weight and cost estimates and to insure that the technology development effort required to bridge the gap between the present and predicted state of the art is properly defined and scoped. Of particular concern are undefined requirements regarding grounds isolation, EMC, cathode to body voltage ripple, and tube arcing energy limiting protection requirements as well as a closer approximation of the voltage and current requirements of the various depressed collectors of the transmitter tube (substantially different requirements were assumed by the two SPS study contractors).

Investigations and laboratory experimentation should be carried out to demonstrate the feasibility of the predicted efficiency and specific weight.

4.2.1 The Technology Readiness of Power Processing

The total weight of the Satellite Power System is projected to be about 35 to 50 x 10^6 kilograms for a 5GW system (with 8GW of power input to the transmitters). This corresponds to a specific power density of 4-6 kg/kW of processed power. This projected weight appears to correspond to a system which will be potentially competitive with future ground based power systems. However, present aerospace power processing technology corresponds to a power density

of the order of 10 kg/kw. Thus the power processing alone, using present technology, weighs more than the total projected system. In addition, present technology will not perform the functions required.

It seems clear therefore that a major effort in power processing technology development is necessary to make future satellite power systems first, technically feasible, and second, economically viable.

4.2.2 Power Processing Equipment

Requirement definition studies, the conceptual design, and weight and efficiency estimates should be updated. Scaled down feasibility test models can be utilized to demonstrate high voltage generation and thermal control, specific weight, and efficiency

4.3 Power Distribution and Processing Components

Necessary technology developments required to advance the state of the art so as to make the SPS concepts technically feasible.

4.3.1 Switch Gear

Three major categories of switch gear have been identified by contractor study as required for SPS operation. These are:

a. Fifty kV, 200-1000 A solar array module switch

b. Fifty kV, 5-10 KA main line switch

c. Fifty kV, 1-10 A high speed (5-10 msec and 5-10 sec) switch

Present aerospace technology provides switch gear capable of switching voltages in the area of 28 to 300V, handling power levels of 25 kW and having operation times to 20 milliseconds. It is

therefore obvious that present technology falls far below the SPS requirements. Without vast improvements in this important technology, the power distribution, processing and management concepts of the SPS cannot be implemented and the survival of the normally arcing transmitter tubes cannot be insured.

4.3.1.1 High Power/High Voltage Switchgear Development Plan

Requirement definition studies, conceptual designs and weight estimates should be updated. Feasibility test models can be utilized to demonstrate high voltage operation, ultrafast overload protection times, and specific weights

4.3.2 Power Device Development

Power electronic devices form the building blocks for switch gear and dc/ac converters and inverters and as such are critical to high performance systems like the SPS. SPS will require new development in areas of:

a. Transformers

b. Inductors

c. Capacitors

d. Diodes

e. SCR's

for operation at 40 kV and ultrahigh power. Present technology is not available for devices operating at the SPS required power levels. Therefore, without new development to these required performance criteria, switch gear and power processing goals will not be met.

4.3.3 Power Transmission

SPS requires transmission of extremely large current (10kA) at potentials of 50 kV over distances of tens of kilometers. Therefore, developments in the areas of:

a. Conductor joining techniques

b. Supports (insulators and stand offs)

c. Surface treatment for heat transfer

d. Equipment/transmission line connectors

are necessary for practical power transmission. The SPS requirements are several orders of magnitude more difficult than present aerospace systems.

Without weight, transmission efficiency and arc protection improvements in these recommended areas of development the SPS will not be able to meet the combined goals of technical feasibility and economic viability.

If adequate consideration is not given to the total power transmission system, catastrophic damage may occur to the equipment on SPS.

4.3.4 Rotary Joints

There are two main rotary joints on SPS. The contractor studies indicate that one joint will require a slip ring, which is 10-15 m in diameter, and the other will require a power cable that can be flexed plus or minus 15°.

It is anticipated that the problems with rotary joints are solvable provided proper attention is given to them early in the SPS program. Consideration shall be given to the use of small ring diameters (1-2 meters) so that the bearings drive mechanisms, fabrication techniques, and other associated problems become easier to manage.

There is the need to develop ring and brush materials that can be operated at high contact temperatures ($200^{\circ}C$). Also brush materials capable of higher current densities than those

proposed by the contractor (7.5 A/Cm^2) are needed. Consideration will be given to the problem of current distribution when multiple brushes are used on the same ring carrying very high currents.

Additional defintion of the flex cable configuration is required. While the angular displacement is only plus or minus 15 degrees, the mechanical properties of this system must be determined, i.e., fatigue of large diameter conductors, mechanical interactions, etc.

4.4 Space Craft Charging and Plasma Interactions

The geostationary orbit plasma environment presents special hazards to spacecraft designers because of the presence of the dense, high temperature plasma associated with the plasma-sheet. Plasma sheet electrons may charge up the satellite to high voltages (of the order of 10 KV). These high voltages may cause breakdown (arcing), damage to components, changes in reflective or thermal control surfaces and possibly shock hazards for EVA and docking activites. Adequate protection techniques have been established for low voltage satellites so that communication satelites have now been built which operate at GEO with no problem.

An associated problem to spacecraft charging is that the ambient space plasma and photoelectrons enter the solar cell array and form a parasitic load.

The voltage that the solar cell array develops attracts plasma ions and electrons to it causing a voltage drop (IR drop) across the cover glass or substrate or blanket support material. Laboratory tests at Lewis Research Center and Johnson Space Center indicate that large surfaces held at positive or negative high voltages tend to arc.

The Marshall Space Flight Center contracted with Rice University for a small study of the space plasma effects on an early Rockwell International SPS design. This study recommended several design modifications and concluded that, with these modifications SPS operation at GEO was probably possible. However, the study stipulated that laboratory and flight testing of specific solar cell arrays operating at high voltage are necessary for a definitive conclusion. This study has not addressed the latest SPS designs using epoxy-graphite composite structures.

The Rice study did not address the separate question of high voltage protection for the high voltages generated by the solar cells themselves and throughout the entire system. The high voltage question is critical to the SPS concept for two reasons: First, the large satellite dimensions require power transfer at high voltage to minimize I^2R losses in the bus bars; second, the use of either klystrons or magnetrons requires high voltages at the device. The solid state sandwich concept is the only SPS concept considered extensively to date which can operate entirely at low voltages.

It is necessary to establish whether or not high voltage (40 KV) solar cell arrays are feasible at GEO on the SPS size scale. There are two parts to this problem, namely, the space plasma interaction question and the design of the system itself to withstand its own high voltage stresses.

The investigation should include a theoretical analysis, possibly computer modeling of the spacecraft fields, laboratory tests of some realistic, arcing protected, solar cell arrays and power distribution devices in a substorm plasma simulator and eventually flight tests in the geostationary orbit. A piggy back ride on another mission to GEO might be possible.

Flight tests should be conducted at LEO to determine the high voltage levels a representative solar array and power distribution devices can tolerate in the LEO environment for use on the EOTV.

4.5 Energy Storage

The objective is to provide power to various SPS components at times when the array is not producing power such as during earth shadow portions of the orbit or shut-down for maintenance. The major portion of this power is needed in the form of thermal energy, i.e., to keep klystron heaters warm (for added life) if klystrons are used to produce the RF power.

The approach suggested by the study contractors was to use batteries or fuel cells. These are straightforward means for providing energy storage. However, the projected requirement of up to 40 MW-hrs of energy will require the battery or fuel cell system to have a high energy

density. Today's best battery technology for synchronous orbit application can be credited to the nickel-hydrogen system with an energy density of 33 W-hr/kg and is projected to reach 66 W-hr/kg with a high confidence level. New battery technology such as the molten salt systems being funded by the DOE for transportation vehicles are also being considered as the next generation space battery. Specific energy estimates for these batteries range from 110 W-hr/kg (Air Force) to 200 W-hr/kg (SPS study contractors). If the requirement of 40 MW-hrs is realistic and if 200 W-hrs/kg is achievable, then 400,000 Kg per SPS system can be saved by supporting the molten salt battery for space application. In concert with using the molten salt battery, thermal management becomes very important. Good thermal management techniques would allow the use of parasitic thermal power to keep the electrolyte hot rather than increasing the solar array size to provide the battery heat.

Another approach to providing thermal power to the klystron heaters is to conceive of a way to use heat pipes (that are now used to cool the klystrons) coupled with a fused salt thermal energy storage capsule that melts the salt during normal operation and freezes the salt, giving up heat to the klystron heater during the time the klystron is not being powered. These thermal energy storage/heat pipe concepts are demostrating 100 W-hr/kg in the laboratory with today's technology and are projected to reach 220 W-hr/kg.

The molten salt electrolyte battery should be designed for space application, cells built and completely characterized. Also, of interest is the corrosion effects associated with the molten salt system that could seriously reduce operational life of the battery.

Likewise if klystrons continue to be the primary means for RF power generation, a study effort is needed to determine if a thermal energy storage/heat pipe configuration makes sense as a means for providing the heat needed by the klystron heater during non-powered periods. Should the concept appear feasible, an effort should be initiated to build and test the combined unit to prove the concept.

4.6 Power Management

The development plan involves conducting power management system (PMS) conceptual design studies to scope the functions and hardware implementation of the PMS including development of the sensors operating at high voltages and of the fiber optics needed for analog and digital data transfer and interfacing with high voltage equipment.

The digital interface units and remote terminal units that will become part of the various power distributions, power processing, energy storage and thermal control equipment should be defined to facilitate their integration into the PMS and SPS.

The PMS of the SPS is required to fulfill the functions of monitoring the quality of critical electric power system parameters, the state and performance of important power distribution, power processing, energy storage and thermal control equipment and take corrective action in case of out-of-tolerance performance or malfunctions. In addition it has to protect the power system elements against destructive overloads, provide protection and recylcing to arcing transmitter tubes and insure safe access of maintenance operations.

The PMS also assists in adjusting the delivered power by the rectenna to the varying load demands of the electric power utility, by adjusting the voltages to the transmitter tubes or by turning off the power to select antenna load centers.

These tasks are performed by gathering data through various types of sensors, analyzing status and trends, predicting electric power generation and generating reconfiguration decisions by means of the electric power system (EPS) data processor.

The EPS data processor interfaces with the electric power distribution and processing system elements through a data bus and remote interface units. Data transmission is accomplished via fiber optics which allows the use of high data rates, provides inherent protection against short circuits to ground and allows optical data transfer across rotary joints.

APPENDIX

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09/11/80